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CONTROL TECHNOLOGY FOR ASPHALT ROOFING INDUSTRY

Industrial Environmental Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
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April 1976

CONTROL TECHNOLOGY
FOR
ASPHALT ROOFING INDUSTRY

by

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Contract No. 68-02-1324, Task 35
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16. ABSTRACT

The report gives results of evaluations of the technical and economic feasibility of candidate control methods which may be capable of 99% removal of total hydrocarbons (HC) emitted from asphalt-saturating and air-blowing operations in asphalt roofing plants, sources of HC emissions for which control technology has not been well characterized. The evaluations were based on information from the literature, theoretical analyses of control systems, and contacts with equipment manufacturers and plant operators. An industry survey showed that thermal incinerators or afterburners are currently the only technique used to control air-blowing emissions. Control techniques for saturator emissions include afterburners, wet scrubbers, high efficiency air filters (HEAF's), and electrostatic precipitators (ESP's). Theoretical analysis of candidate control systems indicated that thermal afterburners, HEAF's, and ESP's could remove 99% of the particulates, but it is doubtful that wet scrubbers could achieve 99% removal. Further device evaluation, to identify candidate devices to be recommended for more research and development, showed that afterburners are already well developed and should be capable of 99% removal; but they cost much more than HEAF's and ESP's and fuel availability could constrain widespread use. The report recommends that pilot scale HEAF's and wet ESP's be tested on an air-blowing source.

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Asphalt Plants	Electrostatic Precipitators	Stationary Sources	
Roofing		Asphalt Saturation	13C
Dust		Air Blowing, Particulate	11G
Hydrocarbons		Thermal Incinerators	07C
Incinerators		Wet Scrubbers	
Afterburners		HEAF Units	21B

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PREFACE

This report was prepared for Industrial Environmental Research Laboratory-RTP, Environmental Protection Agency, to present results of the work carried out by MRI under Contract No. 68-02-1324 (Task 35). This work was performed in the Physical Sciences Division of Midwest Research Institute by Mr. Paul G. Gorman, Dr. K. P. Ananth, Dr. F. Honea, Dr. L. Rust, and Dr. A. K. Rao.

Approved for:

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April 30, 1976

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SUMMARY

Asphalt roofing plants represent a source of hydrocarbon emissions for which control technology has not been well characterized. The technical and economic feasibility of candidate control methods which may be capable of 99% removal of total hydrocarbons emitted from asphalt-saturating and air-blowing operations in asphalt roofing plants was evaluated in this study. Information from the literature, theoretical analysis of control systems, and contacts with equipment manufacturers and plant operators were utilized in making the evaluations.

Results of an industry survey showed that thermal incinerators or afterburners are currently the only technique being employed for control of air-blowing emissions. Control techniques for saturator emissions consist of afterburners, wet scrubbers, filters (HEAF) and electrostatic precipitators.

Analysis of test data for these devices did not reveal any that had demonstrated efficiency as high as 99%. For this reason, it was necessary to employ theoretical analysis to evaluate the capability of various devices for achieving 99% removal of total hydrocarbons. Further, the available test data indicated that emissions from both saturating and air-blowing operations contain considerable amounts of gaseous hydrocarbons, which may range from 2 to 48% of the total hydrocarbons. It would be necessary to effect condensation of these hydrocarbons in order to make it possible for particulate control devices to remove 99% of all hydrocarbons. However, the available data were not sufficient for determining the temperature to which the effluents would have to be cooled for more than 99% of the hydrocarbons to be in particulate form. A current EPA test program should provide more information in this area, but in the interim the assumption was made that precooling below 52°C (125°F) will be required. If the pending test data show that precooling could not achieve the requisite condensation, then afterburners are the only devices that may be capable of achieving 99% removal of total hydrocarbons.

Another concern of this study was removal of POMs, which may be only a small fraction of the total hydrocarbons. However, investigation of previous work in this area indicated that the control devices would be expected to reduce the POM emissions in direct proportion to the particulate removal.

Theoretical analysis of candidate control systems indicated that thermal afterburners, high energy air filters (HEAF) and electrostatic precipitators (ESP) could be capable of 99% removal of particulates, but it is doubtful that wet scrubbers could achieve 99% removal. In addition to the theoretical analysis, further technical and economic evaluations of the devices were performed in order to identify those candidate devices that should be recommended for more research and development. These evaluations showed that afterburners are already well developed and should certainly be capable of 99% removal efficiency, but they have much higher costs than HEAF and ESP units and fuel availability can be a constraint to widespread usage.

HEAF and dry ESP units have already been applied to the control of saturator emissions. Further development work in this area should not be necessary unless the results of the current EPA test program casts serious doubt on their capability for providing 99% removal of particulate matter.

Neither the HEAF nor the ESP units have been used for control of air-blowing emission. It was recognized that the higher grain loadings in air-blowing effluents would increase the filter mat usage rate in a HEAF and could seriously compound the buildup and fouling problems in an ESP. Additional development work is warranted for this application.

Based on the technical and economic evaluations made in this study, several recommendations were made for further research and development efforts and these are presented in the next section. The primary control device development recommendation was that pilot scale HEAF and wet ESP devices be tested on an air-blowing source.

If the HEAF or wet ESP performed successfully on a pilot scale and were proven on a full-scale demonstration project, alternatives to afterburners for high efficiency removal of hydrocarbon emissions from air-blowing operations would be available at lower cost and energy consumption.

CONCLUSIONS AND RECOMMENDATIONS

Inadequate data exist to (a) completely characterize the nature of emissions from saturator and air-blowing operations at asphalt roofing plants, and (b) define the actual performance of candidate control systems. With regard to the former, data are not available to determine the percentage of the hydrocarbon emissions that exist in gaseous form at typical control device operating conditions. Lacking reliable data on the nature of the hydrocarbon emissions, it is difficult to define actual performance of particulate control devices. Based on existing data for other sources, afterburners may be the only method capable of achieving 99% removal of total hydrocarbons.

Theoretical analysis indicated that HEAF and ESP units should be capable of providing 99% removal of particulate hydrocarbons. Cooling of the gases to achieve hydrocarbon condensation prior to entering the HEAF and ESP units may make it possible to achieve 99% removal of total hydrocarbons. Analysis of the performance of wet scrubbers indicated that 99% removal of total hydrocarbons was doubtful.

The principal recommendations for additional work are:

1. Evaluate results of ongoing EPA sampling work as soon as it is completed.

2. Conduct any additional field sampling as may be necessary to characterize emission streams for design of control equipment.

3. Undertake development work to define the performance of HEAF and wet ESP units on air-blowing emissions.

INTRODUCTION

The Clean Air Act directs the Environmental Protection Agency to define and develop technology for control of air pollutant emissions. Much of that effort has been directed to specific industrial source categories. One of these source categories is the asphalt roofing industry.

Preliminary surveys and investigations have indicated that the emissions from sources within this industry are primarily particulate and gaseous hydrocarbons contained in the effluents from the asphalt blowing stills and asphalt saturator operations. The investigations also showed that there were not adequate data available for characterizing these emissions. Application of control devices was very limited on air blowing, but several different types have been applied for controlling saturator emissions, with varying degrees of success.

EPA contracted with MRI to perform a study for evaluation of the technical and economic feasibility of control process candidates for abating air emissions from the asphalt roofing industry.

This study was composed of three parts:

1. Survey the asphalt roofing industry to (a) identify existing control technology, and determine the device usage for controlling air emissions from saturating lines and blowing stills, and (b) identify feasible control process candidates which may be applicable to those sources.

2. For each control process or device identified, determine whether the technology is technically and economically feasible for reducing air emissions by 99%.

3. Recommend the most feasible control process or processes, based on the above evaluation of technical, economic and energy considerations, and determine the cost, time and approach necessary for developing or demonstrating this control technology.

During initial discussions with the project officer (Mr. E. J. Wooldridge) it was mutually agreed that the stipulation of 99% removal efficiency would be defined on the basis of 99% removal of total hydrocarbons. This means all hydrocarbons, whether in the form of solid, liquids, condensible vapor, or gases.

It was logical to assume that the significant emissions from air blowing and saturators would all be hydrocarbons in one form or another, and it was felt that the above definition would be most meaningful. It was also decided that although 99% removal of total hydrocarbons was the primary goal, the devices should also be evaluated on the basis of a lower removal efficiency (e.g., 95%) in order to compare cost differences and other factors.

Although the above definition of removal efficiency (i.e., total hydrocarbons) is probably the most meaningful one for evaluating emission control techniques for the two asphalt industry sources, its use did lead to some difficulties, primarily because of the lack of adequate information on characteristics of emissions from these sources and the associated fact that emission test procedures often do not include determination of gaseous hydrocarbons. Because of the lack of such detailed information it was necessary to make certain assumptions regarding the form and fate of the hydrocarbons. These assumptions are discussed in another section of this report, but basically they consisted of the following:

1. Available test data indicated that for both sources the effluent at stack conditions probably contained a significant portion of gaseous hydrocarbons; probably greater than 5% of the total hydrocarbons. It was therefore assumed that particulate control devices could not provide the required hydrocarbon removal efficiencies unless they were preceded by precoolers (water sprays) to reduce the temperature and maximize condensation of gaseous hydrocarbon constituents.

2. It was further assumed that if the effluent streams are precooled (e.g., water sprays) below 52° C, less than 1% of the hydrocarbons would remain in gaseous form so that 99% removal of total hydrocarbons would be possible via particulate control devices if this were within their capability and they were so designed.

This latter assumption is rather tenuous. Another EPA project that is currently in progress involves testing of various control devices currently used in asphalt roofing plants and the test method being used should provide more information on the percent gaseous hydrocarbons at the sampling temperature of 38° C. If data obtained in that project do not validate the above assumption, some of the results in this report may need to be reconsidered. That is, it would not be appropriate to pursue further testing and development of control devices that remove only the particulate matter.

Details of the various activities on the program are presented in the following sections of this report.

DISCUSSION

SURVEY OF THE INDUSTRY

Initial work on this project consisted of a survey of the industry to (a) identify the extent of usage and capability of current control devices used to control emissions from asphalt-blowing operations and saturator lines, and (b) identify other possible control techniques. Activity also included collection of existing data to characterize the emissions and control techniques for the two emission sources. The major outputs from the survey are presented in the following subsections.

Process Descriptions

Figures 1 and 2 illustrate the asphalt-blowing operations and the saturator lines. Air blowing is a batch operation in which compressed air is forced to bubble up through the liquid, at temperatures of 220 to 270°C, for a period of about 2 to 4 hr or longer in horizontal stills. The purpose of this operation is dehydrogenation, causing some polymerization of the asphalt to increase its melting point.1/ The longer the blowing time the higher the melting point, and the length of time is dependent on whether the asphalt is to be used as saturant or coating in the saturating line. The blowing operation uses 0.006 to 0.06 m^3/min of air per gallon of asphalt and the quantity of asphalt to be blown is on the order of 20 to 40,000 liters. Water may also be added at the top of the vessel to form steam to blanket the liquid surface and maintain proper temperatures of the asphalt. Effluent flow rates may therefore be approximately 140 to 560 m^3/min at a temperature of about 170 to 200°C.

The effluent gas from the blowing stills is composed primarily of unreacted air and water vapor but also contains carbon oxides and some sulfur compounds plus gaseous hydrocarbons and entrained asphalt droplets. This effluent is usually passed through a cyclone separator to collect the larger droplets, presumably those that are greater than 10 μm in size. This recovered material may be drained back into the blowing vessel, mixed with raw asphalt or burned in one of the asphalt heaters. The exhaust from the cyclone is then ducted to an afterburner or a process heater furnace.

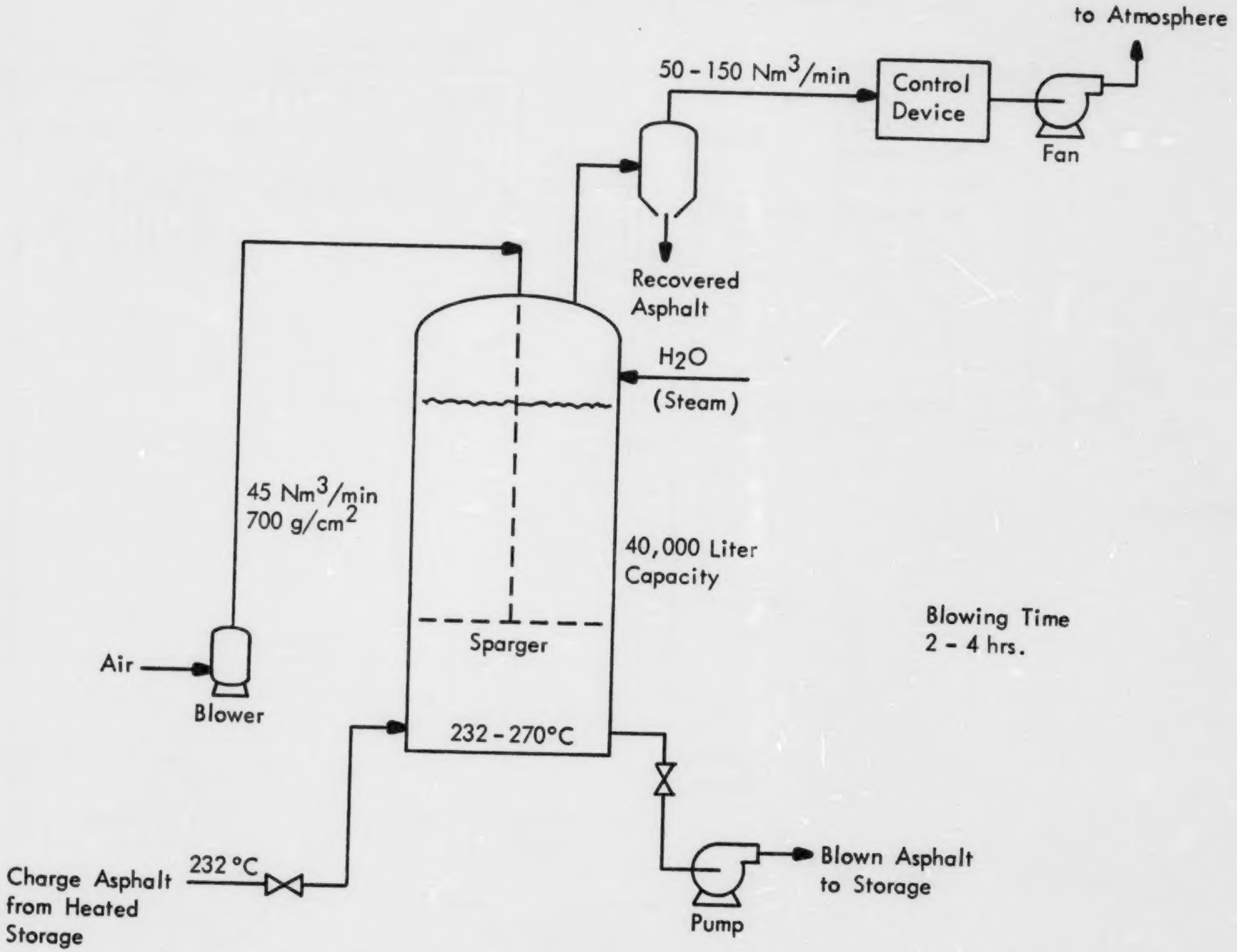
to Atmosphere
50 - 150 Nm^3/min
Control Device
Fan
Recovered Asphalt
H_2O
(Steam)
45 Nm^3/min
700 g/cm^2
40,000 Liter Capacity
Blowing Time
2 - 4 hrs.
Air
Blower
Sparger
232 - 270°C
Charge Asphalt from Heated Storage
232 °C
Pump
Blown Asphalt to Storage

Figure 1. Schematic Diagram of Vertical Asphalt Blowing Still

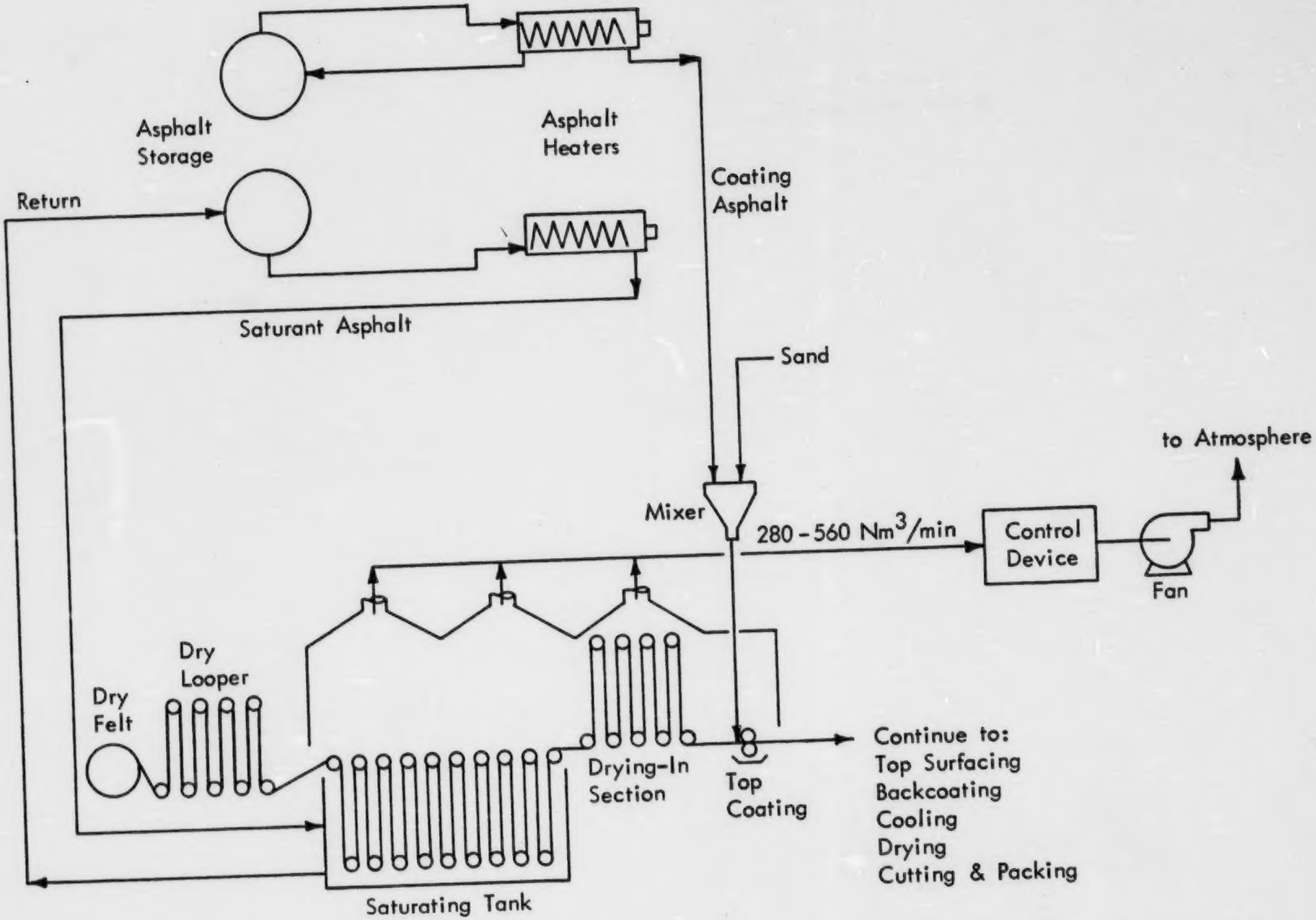
Asphalt Storage
Asphalt Heaters
Coating Asphalt
Return
Saturant Asphalt
Sand
Mixer
280 - 560 Nm^3/min
Control Device
Fan
to Atmosphere
Dry Felt
Dry Looper
Saturating Tank
Drying-In Section
Top Coating
Continue to:
Top Surfacing
Backcoating
Cooling
Drying
Cutting & Packing

Figure 2. Schematic Diagram of Asphalt Saturating Line

Saturator lines consist of dip tanks or sprays, or both, where the saturant is applied to the felt. The saturated felt passes through a drying-in section followed by application of coating asphalt to one side of the saturated felt. Although mechanical problems or breakage of the felt may cause intermittent shutdowns of the saturating line, it is essentially a continuous operation.

These saturating and coating operations may be partially or totally enclosed with air and fumes being exhausted from the enclosure to a control device (or directly to atmosphere). The volume of effluent exhausted is on the order of 560 Nm^3/min and consists primarily of air, water vapor, asphalt liquid droplets (fume) and gaseous hydrocarbons.

Variations in process and operating parameter do affect resultant emissions. Air-blowing emissions are generally lower from vertical stills, but the emissions are also a function of the asphalt feedstock, blowing rates and temperatures, and the meltpoint of the desired product. Saturating line emissions are affected by indraft air and hooding arrangements, but are also influenced by the characteristics of the asphalt and the felt, as well as variations in the spraying/dipping process and line speeds, etc.

Control Practices

One of the first steps in this study was to identify the types of control equipment presently being used to control emissions from air-blowing and saturator operations and determine the extent that they have been applied to these two sources. A survey of the industry disclosed that all blowing stills are controlled to some degree, either by ducting the fume to a direct fired process heater or ducting them to an afterburner. However, other information indicated that only about 40% of the plants do their own blowing. With regard to the extent of control of asphalt saturators, the MRI survey of 76 saturators showed the following:

Number of saturators	Control devices
28	Afterburners
18	HEAF
10	Electrostatic precipitator
9	Wet scrubber
11	Uncontrolled
76	

It was found that all of the air-blowing operations are controlled by some means of fume incineration, whether by ducting of the fume to process heaters or installation of afterburners. However, it is possible that the process heater control method might not provide the same destruction of hydrocarbons as an afterburner (i.e., proper operating temperatures and residence time). It was also noted that in some cases an afterburner may be used to control emissions from both the air blowing and saturators, but to our knowledge fume incineration techniques are the only method that has been used, or tried, for control of air blowing operations. On the other hand, several types of devices have been installed for control of asphalt saturator emissions. A list of all asphalt roofing plants is given in Appendix A, with partial information on control equipment.

In order to evaluate the control techniques that are being used, a search of the literature and other sources was made in an attempt to characterize the emissions from air blowing and saturators, and to compile results of the test data on the control devices, as discussed in the next section.

Characterization of Emissions

A search of the literature was carried out in order to compile available data on air blowing and saturator effluents and compile test data for determining efficiency of control devices. One of the reasons for compiling this type of data was to form a basis for selecting representative effluent characteristics for a plant model that could be used as a common basis for evaluating the technical and economic feasibility of all types of candidate control techniques.

Results of the above data compilation work are presented in Tables 1 and 2. For air blowing operations, these data showed that uncontrolled particulate concentrations (which included condensible particulate) ranged from 3.0 to 25.6 g/Nm^3. Gaseous hydrocarbon content was determined separately in some of these tests but because of the sampling methods used, it is difficult to determine how much of these gaseous hydrocarbons may have been collected as condensible particulate. Even so, the magnitude of the gaseous hydrocarbon quantities indicate that a significant portion (> 1%) of the emissions are probably in gaseous form.

These same data also showed that the removal efficiency of the afterburners (process heaters) ranged from 84.6 to 95.8%, which is lower than might have been expected. The reason for this cannot be definitely determined, but it is suspected that these process heaters, which served as afterburners, probably did not provide proper mixing, operating temperature, and residence time for efficient destruction of the asphalt hydrocarbons. In such heaters, firebox temperature is usually controlled by the exit temperature of the asphalt, so control efficiency may be reduced when firebox temperature is reduced.[2/]

Our examination of the literature did not reveal any data on particle size distribution of the air-blowing emissions. It should be noted that the air-blowing emissions are at higher temperatures (94 to 153° C), and

Table 1. SUMMARY OF TEST DATA REPORTED FOR BLOWING EMISSIONS

Data source	Inlet					Control device	Outlet			Control eff. (%)
	Gas flow (Nm^3/min)	Temp. (°C)	Conc. (g/Nm^3) F. part.d/	Conc. (g/Nm^3) F. part. and cond.e/	Emissionsf/ (kg/hr)		Conc. (g/Nm^3) F. part.d/	Conc. (g/Nm^3) F. part. and cond.e/	Emissionsf/ (kg/hr)	
1/	62.3	153	-	25.6	96b/	ABa/	-	0.23	4.0b/	95.8
1/	62.3	94-99	-	3.39-8.15	11-32.5b/	ABa/	-	0.053-0.275	0.86-5.0b/	84.6-94.5
2/	238.0	99	-	2.97	42.5c/	None				

---

a/ Control device was a fume incinerator used to preheat asphalt.

b/ Separate tests for gaseous HC's showed average values of 15.9 mg/hr at the inlets and 8.5 kg/hr at the outlet. However, it is not possible to determine what portion of these "gaseous" hydrocarbons, if any, may have been collected and reported as condensible particulates.

c/ Samples collected in plastic bags and analyzed by FID showed 2,500 ppm gaseous HC at room temperature. This would be equivalent to about 24 kg/hr. However, the special particulate sampling method, intended for POM, cools the sample stream to -18°C so may include some of the "gaseous HC" as condensible vapor.

d/ Filterable particulate.

e/ Filterable particulate and condensibles.

f/ Total emission rate, in kg/hr, comprised of both filterable particulate and condensibles whenever such data were available.

1/ Gerstle, R. W., "Atmospheric Emissions from Asphalt Roofing Processes," EPA Report No. EPA-650/2-74-101, pp. 51 and 56, October 1974.

2/ Von Lehmden, D. J., R. P. Hongebrauck, and J. E. Meeker, "Polynuclear Hydrocarbon Emissions from Selected Industrial Processes," J. Air Pol. Cont. Assn., 15:7, July 1965.

Table 2. SUMMARY OF TEST DATA REPORTED FOR SATURATOR EMISSIONS

	Inlet (uncontrolled)						Outlet					
			Conc. (g/Nm³)						Conc. (g/Nm³)			
Data source	Gas flow (Nm³/min)	Temp. (°C)	F. part.a/	F. part. and cond.b/	Emissionsc/ (kg/hr)	Control device (with precooling)	Gas flow (Nm³/min)	Temp. (°C)	F. part.a/	F. part. and cond.b/	Emissionsc/ (kg/hr)	Control eff. (%)
1/												
1/	354	54	-	1.35	28.6							
1/	286	127	-	1.81	30.9							
1/	773	53-57	0.18-0.23	-	8.6-10.9							
1/, 2/	340	59	-	1.224	25	Scrubber (H_2O)	345	28	-	0.169	3.5	86.0
3/	- - - - - Inlet not tested - - - - - - - - - - - - - - - -					Scrubber ($KMnO_4$)	652	32	0.016	-	0.62	-
1/, 2/	567	60	-	0.952	32.3	Scrubber and ESP	570	28	-	0.133	4.5	86
4/	595	52-61	0.034	0.066	2.4	ESP (no)	425	49	0.0041	0.025	0.60	74.4
4/	708	53-58	0.080	0.101	4.3	ESP (no)	538	52	0.0059	0.043	1.40	67.7
5/	575	33	0.114	0.162	5.56	ESP (unknown)	595	32	0.0014	0.0076	0.27	95.2
6/	391	(Unknown - see outlets)	-	1.227	27.4	HEAF (no)	(See inlets)	48	-	0.1293	3.3	88
	317		-	0.602	11.2	HEAF (no)		64	-	0.0494	0.91d/	92
	1,195		-	0.863	14.1	HEAF (no)		69	-	0.0208	1.00d/	93
	844		-	0.897	12.0	HEAF (no)		56	-	0.0188	0.73	94
1/	940	58-74	-	0.11-0.73	6.8-37.3e/	HEAF (no)	-	54-80	-	0.037-0.183	1.86-9.68e/	67.2-92.8
1/	297	60-92	-	0.69-1.08	12.3-15.4e/	ABf/	-	593-677	-	0.183-0.275	4.23-8.05e/	34.4-72.6
7/	173	99	-	1.146	11.9	ABf/	249	393	-	0.076	1.14	90.4

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a/ Filterable particulate.

b/ Filterable particulate and condensible particulate.

c/ Total emission rate, in kg/hr, comprised of both filterable and condensible particulate whenever such data were available.

d/ Two tests included sampling for gaseous hydrocarbons, showing these to be 0.27 and 1.95 kg/hr, but it could not be determined what portion of these may have been collected and reported as condensible particulates.

e/ Separate tests for gaseous hydrocarbons (HC) showed average values of 1.0 and 1.9 kg/hr at the inlets with 1.14 and 2.50 kg/hr at the outlets, respectively. However, it was not possible to determine what portion of these gaseous hydrocarbons, if any, may have been collected and reported at condensible particulates.

f/ Control device was a process heater furnace.

1/ Gerstle, R. W., "Atmospheric Emissions from Asphalt Roofing Processes," EPA Report No. EPA-650/2-74-101, pp. 37 and 38, October 1974.

2/ Weiss, S. M., Air Pollution Engineering Manual, Public Health Service Publication 999-AP-40 (1967).

3/ White, H. R., Source Emission Test Report by Alar Engineering Corporation (Chicago, Illinois) for Fry Roofing Company of Brookville, Indiana, dated July 23, 1974.

4/ DeWees, W., and R. Gerstle, Emission Test Report by PEDCo-Environmental (Cincinnati, Ohio) for the Celotex Corporation of Lockland, Ohio, dated April 1974.

5/ DeWees, W., and R. Gerstle, Emission Test Report by PEDCo-Environmental (Cincinnati, Ohio) for the Celotex Corporation of Fairfield, Alabama, dated March 1975.

6/ Netzley, A. B., "Control of Asphalt Saturators by Filtration," paper presented at the 68th annual meeting of the Air Pollution Control Association, Boston, Massachusetts, June 15 to 20, 1975.

7/ Nance, J., and W. L. Oaks, Emission Test Report No. C-2095 by Los Angeles Air Pollution Control District at Bird and Son, Inc., of Wilmington, California, dated January 10, 1974.

have higher grain loadings than saturator emissions. Opinions have also been expressed that the asphalt emissions from air blowing are of a more tar-like nature than those from saturator operations.

Data for saturator operations (Table 2) showed a wide variation in uncontrolled grain loading of 0.066 to 1.81 g/Nm^3. From those tests that included determinations of both filterable and condensible particulate, it is indicated that the percentage of hydrocarbons that exist in vapor form in the stack is significant; being no less than 2% and as high as 48%. Some information is available on the particle size distribution for saturator emissions (Figure 3) indicating a median particle diameter of about 0.8 µm.

Reported efficiencies of particulate (and condensible hydrocarbons) removal for the various types of control devices were as follows:

Control device	Range of particulate removal efficiency[a]
Afterburners	34.4-90.4%
ESP	74.4-95.2%
HEAF	62.7-94%
Wet scrubber	86%

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[a] Removal efficiency for filterable particulate and condensible hydrocarbons.

Most of the above efficiency data did not include analysis for gaseous hydrocarbons so these values do not necessarily reflect total hydrocarbon removal efficiency.

In some cases, the control system employed on saturator emissions includes some type of precooling, usually water sprays, which are believed to enhance control efficiency. This is consistent with the expectation that precooling would promote condensation and particle size growth for the hydrocarbon emissions, thereby improving collection efficiency. However, it is difficult to quantify such effects because sufficient test data were not available (i.e., efficiency tests with and without precooling).

Nature of Gaseous Hydrocarbon Emissions

Some of the emission tests on air blowing and saturators did include sampling and analysis of gaseous hydrocarbons. This was usually done in conjunction with the tests for filterable and condensible particulates.

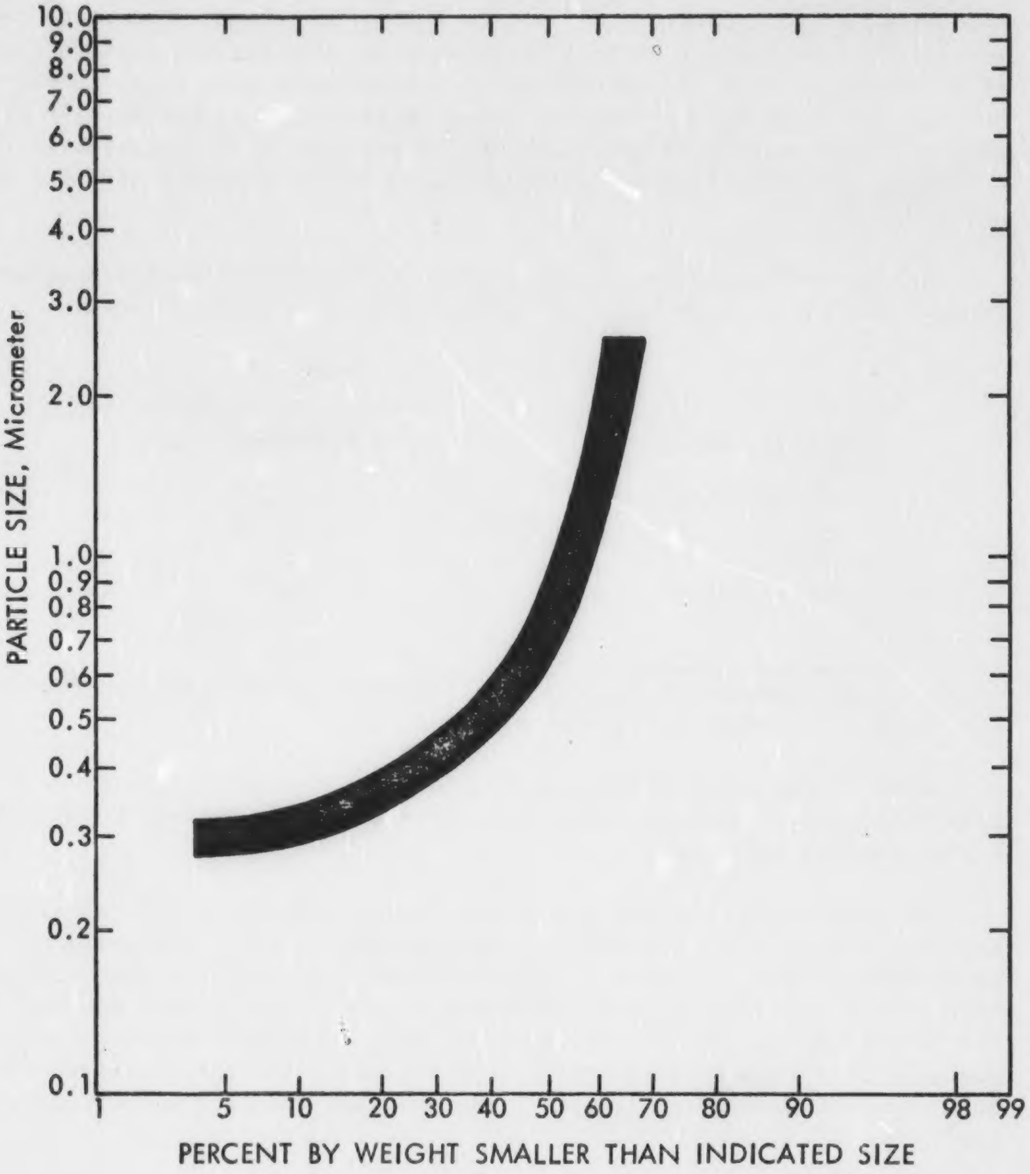

Figure 3. Particle Size Distribution[2] in Uncontrolled Saturator Exhaust

These gaseous hydrocarbon tests were based on samples collected in plastic bags that were later analyzed by flame ionization detectors. Such samples probably also included some of the liquid droplets so it is difficult to interpret the results in terms of how much gaseous hydrocarbons would remain in the normal sampling train after all filterable and condensible hydrocarbon had been removed. Even so, the test data in Tables 1 and 2 do shed some light on the problem.

Data for air blowing in tests conducted by PEDCo[2/] showed that the controlled HC emissions exceeded the total of filterable and condensible particulate. However, the control devices were process heaters, so the gaseous hydrocarbon data could be very misleading.

The same set of data for uncontrolled emissions showed gaseous HC values of 14.7 and 16.7 kg/hr while the filterable and condensible particulate for all tests averaged 32.1 kg/hr. As mentioned earlier, these data cannot necessarily be interpreted to mean that gaseous hydrocarbons amount to about 50% of the total filterable and condensible material. On the other hand, the data do support the assumption that the uncontrolled effluent contains a significant portion of gaseous hydrocarbons, especially considering the process and temperatures involved (232 to 260° C).

Considerably more test data were available for saturator effluent and associated control devices. Three of these tests, when averaged, showed filterable particulate concentrations of 0.075 g/Nm^3 while respective total particulate (filterable and condensible) concentrations averaged 0.110 g/Nm^3. These data would indicate that the condensible vapors were 31% of the total. However, since the total concentrations for these tests were much lower than several of the other test data ($\approx$ 0.7 to 1.1 g/Nm^3) it would be possible to argue that the percentage of condensible vapors might be much lower (i.e., 2%) but this is still a significant amount relative to the objective of 99% removal of all hydrocarbons. Therefore, it certainly is reasonable to assume that the effluent from both air blowing and saturators contain gaseous hydrocarbons in sufficient proportions (> 1%) such that particulate removal devices could not achieve 99% removal efficiencies unless some means could be provided to reduce the gaseous hydrocarbons to less than 1% of the total hydrocarbons.

It would, of course, be expected that precooling of effluent gases would cause condensation of gaseous hydrocarbon. Very little data were available on the two emission sources of interest that could be utilized to determine how low a temperature would be necessary. The only data that were available are that from Refs. 4 and 5 shown in Table 2.

Data from Ref. 5 is the most interesting because of the low operating temperatures (33°C). Inlet concentrations showed 0.048 g/Nm^3 of condensible particulate at 33°C while outlet concentrations showed 0.0062 g/Nm^3 at 32°C. This would indicate that the control device (an ESP) was removing most of the gaseous hydrocarbons, which is highly unlikely. It is more probable that these data reflect the sampling problems associated with this source. That is, liquid collected on the filter seeps through the filter, is carried over into the impingers, and is reported as condensible particulate.

Considering such problems as those discussed above and previous discussion of difficulties in interpreting the gaseous hydrocarbon sampling data, it must be concluded that sufficient information is not available for determining the temperature to which the effluent streams would have to be cooled in order that less than 1% of total hydrocarbons would remain in gaseous form. Further, within the normal range of temperatures, it may be that this is not possible at all. However, a current EPA sampling program utilizes sampling and analyses methods that should provide considerably more information in this area. This method requires that the effluent sample be cooled to 38°C with collection of the filterable and condensible particulate on fiberglass. It is then passed through a final filter and remaining hydrocarbon gases determined by FID (flame ionization detector).[8] Results from this sampling method should provide a considerable amount of data on the percent of total hydrocarbons that remain in gaseous form at 38°C. In the interim, it has been assumed that less than 1% of the total hydrocarbons will remain in gaseous form if the effluent streams are cooled below 52°C.

POM Emissions

Control devices considered in this study were to be evaluated on the basis of total hydrocarbon removal efficiency, as stipulated earlier. It must be realized, however, that this does not directly address removal of POM, which may be of concern. These compounds comprise a very small portion ($\ll$ 1%) of the total hydrocarbons.[2] Therefore, even if a device provided 99% removal of total hydrocarbons it might provide negligible control of POMs.

It might be suspected that the air-blowing operations would be a more significant source of POM than saturators. Tests reported by Hangebrauck[3] on POM emissions from air blowing led him to conclude that the process does not appear to emit significant amounts of BaP or other POMs of equal or greater molecular weight, as compared to the quantities emitted by other sources and effects on ambient air levels. He noted, however, that it does emit large quantities of unidentified alkyl polynuclear hydrocarbons which might be carcinogenic.

With regard to removal of POM via control devices, test reported by PEDCo[2] showed that in most cases the control methods reduced the POM in direct proportion to the particulate removal. This led them to conclude that it does not appear that roofing plants with typical controls are a major contributor of these compounds (POM) to the ambient air.

Removal of POMs by "typical controls" as reported by PEDCo is consistent with that found by Hangebrauck in studies of other industrial processes. It was found that combustion of the emissions (afterburning) or wet scrubbing considerably reduced these emissions (> 90% reductions). Similar work by Cuffe[4] mentions that fly ash collectors in coal-fired power plants (e.g., electrostatic precipitators) showed significant collection of POM, which was attributed to the expectation that POMs are, or are associated with, particulate matter that is removed by the collectors.

Based on the foregoing information, we concluded that high efficiency control devices (99%) applied to asphalt blowing and saturator emissions would also provide high efficiency removal of POMs.

It is important to mention that the PEDCo report[2] showed that in tests on a process heater furnace used to control saturator emissions, there was no decrease in POMs. Again, it is suspected that this oil-fired process heater did not provide proper operating conditions for efficient destruction of hydrocarbons, including POM. As mentioned earlier, properly designed afterburners should provide efficient removal of these compounds. The current EPA test program does include testing for POMs and should provide additional information in this area.

TECHNICAL AND ECONOMIC EVALUATION OF CANDIDATE CONTROL TECHNIQUES

The industry survey information discussed previously was used to identify candidate control techniques and available data on these control devices. This information was combined with engineering analysis and cost estimates in order to evaluate the technical and economic feasibility for 95 and 99% removal of total hydrocarbons.

The industry survey revealed that the only control technique that is being used or has been tried on air-blowing emissions is thermal incineration (afterburners). For saturator emissions control, several techniques are being used, and include afterburners, electrostatic precipitators, filters (HEAF) and wet scrubbers. These devices were included in the technical and economic evaluations, but other possible control methods were also given at least preliminary consideration. Possible methods considered were wet electrostatic precipitators and catalytic afterburners. The technical and economic evaluations for all control methods basically consisted of three areas:

1. Theoretical and engineering analysis of their capability for 95 and 99% removal of total hydrocarbons.

2. Estimates of capital, operating and annualized costs.

3. Tabulation of energy requirements, waste disposal aspects, operating problems, and other advantages and disadvantages including their applicability for controlling both emissions sources (air blowing and saturating lines).

Control efficiency for all devices except afterburners was based on the assumption that use of precoolers would provide for more than 99% of the hydrocarbons being in particulate form.

In order to provide a common basis for evaluating the control devices, certain criteria were selected from the industry survey data to represent a plant model. These criteria are shown in Table 3. Specific cost estimation criteria were also set out as follows:

Depreciation period	15 years (straight line)
Interest and taxes	9%
Utilities	
Natural gas	\$1.222/10^9 joules
Fuel oil	\$2.63/10^9 joules
Electrical	\$0.016/kw-hr
Operating time	5,480 hr/year for saturator controls
	2,080 hr/year for blowing controls

Most of the actual test data on the control devices were not sufficient for determining whether a specific type of device was or was not capable of 95 or 99% removal efficiency. It was, therefore, necessary to employ theoretical analysis techniques for this purpose. These techniques usually necessitated use of particle size distribution data, some of which were available for saturator emissions. No such data were available for air-blowing emissions, but it seems reasonable to assume that the saturator emissions represent a control problem no less difficult to control than air-blowing emissions because for saturators the grain loading is low and the mean particle diameter is quite small (0.8 μm).

Details of the technical and economic analysis, calculations that were carried out for specific types of control devices, descriptions of the devices and their characteristics are presented in Appendices B, C, D, and E.

Results of the technical and economic analyses, along with other information considered important for comparison purposes, have been tabulated and are presented in Tables 4 and 5. A listing of advantages and disadvantages is given in Table 6.

Table 3. SELECTED EMISSION CRITERIA

	Range of avilable data	Selected value
Saturator emissions		
Gas flow	173-1,195 Nm^3/min	567 Nm^3/min
Temperature	33-127° C	68° C
Grain loading	0.066-1.81 g/Nm^3	0.80 g/Nm^3
Moisture content	1.5-3.8%	3%
Blowing emissions		
Gas flow	62-567 Nm^3/min	567 Nm^3/min[a]
Temperature	94-153° C	121° C
Grain loading	3.0-25.6 g/Nm^3	8.4 g/Nm^3
Moisture content	5.1-19.5%	16%

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[a] Gas flow of 567 Nm^3/min was selected to represent control devices designed for control of more than one air blowing vessel and to facilitate comparison with saturator controls.

Table 4. EVALUATION OF CONTROL EQUIPMENT FOR ASPHALT SATURATOR EMISSIONS

	Afterburners				HEAF		Electrostatic precipitators				Wet scrubbers	
	Thermal		Catalytic				Wet		Dry			
	95%	99%	95%	99%	95%	99%	95%	99%	95%	99%	95%	99%
A. Collection efficiency for total hydrocarbons. (Refers to collection of particulate hydrocarbon equivalent to precooling to 52°C.) Indicate need to precool (Yes or No).	No	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes	No	No
B. Can specified efficiency be reasonably expected without being preceded by other control devices, except cyclones and/or precooling (Yes or No).	Yes	Yes	No	No	Yes	Unknown	Yes		Yes		No	No
C. Estimated costs[e]			Removal costs comparable with thermal afterburners (higher capital cost but lower fuel costs)								No further information listed, because analysis indicates that required efficiency cannot be reasonably achieved.	
Installed cost, $	312,000[a]	327,000[a]			100,000[c,f]		169,000[d,f]		85,000[d,f]	113,000[d,f]		
Operating cost, $/year	61,200[b]	63,900[b]			19,000[c]		5,500[d]		5,500[d]	6,000[d]		
Annualized cost, $/year	110,000[a,b]	116,000[a,b]			34,700[c,f]		32,000[d,f]		18,800[d,f]	23,700[d,f]		
D. Does system generate other effluent problems (Yes or No - and what type).	No		No		Yes (Disposal of used mats and precooling effluents)		Yes		Some (periodic washing)			
E. Has similar system been operated on this source (Yes or No). If yes, at what range of particulate collection efficiency.	Yes (34 to over 90%)		No		Yes (88 to 92%)		No		Yes (74 to 95%)			
F. Are plugging, poisoning, or other problems considered likely (Yes or No). Specify if yes.	No		Yes (Potential plugging and poisoning of catalyst bed with asphalt liquid particles)		No		Unknown		No			

Table 4. (concluded)

	Afterburners						Electrostatic precipitators					
	Thermal		Catalytic		HEAF		Wet		Dry		Wet scrubbers	
	95%	99%	95%	99%	95%	99%	95%	99%	95%	99%	95%	99%
G. Is device amenable to controlling both types of sources (airblowing and saturator) (Yes or No).	Yes		No (Unless preceded with filter to remove asphalt liquid particles)		Unknown		Unknown		No		No further information listed, because analysis indicates that required efficiency cannot be reasonably achieved.	
H. Energy Required (for 567 Nm^3/min) 10^9 joules/hr												
- Electrical Power	None	None	0.033	~ 0.07	0.57		≈ 0.13					
- Natural Gas or Oil	38.2	39.9		~ 30.8	None		None					
- Other	(max. without heat recovery)		(Max. without heat recovery)		None		Negligible					
I. Process Availability (Proprietary or NonProprietary)	NP	NP	P	P	P	P	NP	NP	NP	NP		
J. Are any design or operating parameters near or outside practical limits of the required efficiency. (Yes or No).	No	No	Yes, temperature and catalyst bed volume are near maximums at 95% removal		No	Unknown	No					
K. Are there any unique operating or maintenance requirements (Yes or No). Identify if yes.	No	No	Unknown		No	Unknown	Unknown		Yes. Fouling of electrodes due to asphalt liquid particles			

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a/ Installed cost based on 80% heat recovery, because this represents lowest annualized cost (see Appendix B).
b/ Operating cost with natural gas fuel.
c/ For more information on HEAF cost estimates see Appendix C.
d/ For more information on ESP cost estimates see Appendix E.
e/ Costs do not include any additional operating labor.
f/ Includes costs for precooling the effluent to effect condensation.

Table 5. EVALUATION OF CONTROL EQUIPMENT FOR AIR BLOWING EMISSIONS

	Afterburners				HEAF		Electrostatic precipitators				Wet scrubbers	
	Thermal		Catalytic				Wet		Dry			
	95%	99%	95%	99%	95%	99%	95%	99%	95%	99%	95%	99%
A. Collection efficiency for total hydrocarbons. (Refers to collection of particulate hydrocarbon equivalent to precooling to 52°C.) Indicate need to precool (Yes or No).	No	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes	No	No
B. Can specified efficiency be reasonably expected without being preceded by other control devices, except cyclones and/or precooling (Yes or No).	Yes	Yes	No (HEAF unit recommended in front)	No	Unknown		Unknown				No	No
C. Estimated costs[f] Installed cost, $ Operating cost, $/year Annualized cost, $/year	290,000[a] 24,500[b] 69,900[a,b]	304,000[a] 25,400[b] 73,000[a,b]	Costs comparable with thermal afterburner (higher capital cost but lower fuel cost)		100,000[c,g] 20,700[c] 36,400[c,g]		169,000[d,g] 5,500[d] 32,000[d,g]		[e]		No further information listed, because analysis indicates that required efficiency cannot be reasonably achieved	
D. Does system generate other effluent problems (Yes or No - and what type).	No		No		Yes (Disposal of used mats and precooling effluents)							
E. Has similar system been operated on this source (Yes or No). If yes, at what range of particulate collection efficiency.	Yes (85 to over 95%)		No		No		No		No			
F. Are plugging, poisoning, or other problems considered likely (Yes or No). Specify if yes.	No		Yes (Potential plugging and poisoning of catalyst bed with asphalt liquid particles)		Possibly (Plugging of mat)		Unknown		Yes (Fouling of electrodes is expected to be a serious problem)			

Table 5. (concluded)

	Afterburners				HEAF		Electrostatic precipitators				Wet scrubbers	
	Thermal		Catalytic				Wet		Dry			
	95%	99%	95%	99%	95%	99%	95%	99%	95%	99%	95%	99%
G. Is device amenable controlling both types of sources (air blowing and saturator) (Yes or No)	Yes		No (unless preceded with filter to remove asphalt liquid particles)		Unknown		Unknown		No		No further information listed because analysis indicates that required efficiency cannot be reasonably achieved.	
H. Energy Required (for 567 Nm^3/min) 10^9 joules/hr												
- Electrical Power	None	None	0.033	~ 0.07	0.57		≈ 0.13					
- Natural Gas or Oil	35.6	37.2	27.3	~ 28.8	None		None					
- Other	(max. without heat recovery)		(max. without heat recovery)		None		Negligible					
I. Process Availability (Proprietary or NonProprietary)	NP	NP	P	P	P	P	NP	NP	NP	NP		
J. Are any design or operating parameters near or outside practical limits of the device, for the required efficiency. (Yes or No).	No	No	Yes, temperature and catalyst bed volume are near maximums at 95% removal.		Unknown		Unknown					
K. Are there any unique operating or maintenance requirements (Yes or No). Identify if yes.	No	No	Unknown		Unknown		Unknown		Yes (Fouling of electrodes)			

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a/ Installed cost based on 80% heat recovery because this represents lowest annualized cost (see Appendix B).
b/ Operating cost with natural gas fuel.
c/ For more information on HEAF cost estimates see Appendix C.
d/ For more information on ESP cost estimates see Appendix E.
e/ Costs may be about the same as for saturators but dry ESP's are not thought to be applicable to air blowing.
f/ Costs do not include any additional operating labor.
g/ Includes costs for precooling the effluent to effect condensation.

Table 6a. AFTERBURNER ADVANTAGES AND DISADVANTAGES

	Thermal		Catalytic	
	Advantages	Disadvantages	Advantages	Disadvantages
Technical considerations	· Presently used in the asphalt roofing industry. · Removal efficiency from 89 to over 95%. · 99% removal efficiency is possible with little increase in fuel consumption. · Capable of controlling emissions from blowing and saturators. · Low maintenance requirements. · Long operating life. · Available designs and hardware. · No secondary wastes are generated.	· Fuel availability is a potential problem.	· Lower operating temperature than thermal afterburner saves fuel. · Can achieve over 95% removal efficiency.	· Potential plugging and poisoning of catalyst bed. · HEAF unit recommended to precede catalytic afterburner to prevent plugging. (Requires high pressure drop.) · Design and development tests are required. · Fuel availability.
Economic considerations	· Low maintenance costs. · Operating cost may be quite small if recovered energy (steam) is required by plant.	· Fuel cost is high especially if no heat recovery system is used. · Capital cost is high.	· Lower fuel cost than for thermal afterburner (custom design and catalyst costs). · Potential low maintenance costs. · Potential recovery of spent catalyst.	· HEAF unit may also be required at added cost. · Fuel costs are high with no heat recovery system. · Increased electric fan power costs over thermal afterburner. · Potential long-lead delivery time for development. · Higher capital cost.

Table 6b. HEAF ADVANTAGES AND DISADVANTAGES

	Advantages	Disadvantages
Technical considerations	· Presently used in roofing industry (saturators) · Capable of obtaining high collection efficiencies (87 to 94% on particulates). · Available designs and hardware. · Ease of maintenance and operation. · Operation of unit dependent only on electrical power.	· Not capable of controlling gaseous hydrocarbons. · Requires cooling of inlet gases to maximize collection of condensible particulates. This adds to maintenance and operating requirements. · Requires frequent replacement of fiber mats. · Disposal of used fiber mats is a potential problem.
Economic considerations	· Lower cost than afterburner. · Mat costs are low.	· With water cooling, maintenance/operation costs probably will increase and resultant liquid may need to be treated.

Table 6c. ELECTROSTATIC PRECIPITATOR ADVANTAGES AND DISADVANTAGES

	Advantages	Disadvantages
Technical considerations	· Have been used successfully in asphalt roofing industry on saturators. · Modular design allows achievement of high removal efficiency (up to 99%). · Long operating life. · Available designs and hardware. · Wet-wall units may be applicable to blowing operations.	· Precooling is probably necessary to condense gaseous hydrocarbons. · Dry unit not applicable to blowing operations because it is expected that higher grain loading would result in excessive fouling of electrodes. · Secondary water treatment may be required for wet-wall units. · Further testing required on wet-wall units for saturator/blowing operations. · Requires frequent cleaning.
Economic considerations	· Lowest operating cost. · Low maintenance cost. · Lower capital cost than afterburners.	

A summary of results and interpretation of this and other information are presented in the following paragraphs for each type of device.

Afterburners

Theoretical analysis of thermal afterburners indicated that properly designed units (0.3 sec residence time at 816°C) should be capable of providing 99% removal of total hydrocarbons. However, in comparison with other types of devices, their capital cost is high. Also, due to the fuel requirements their operating costs are also high. Of course, these operating costs are a function of the heat recovery equipment that may be used, but such equipment increases the capital cost. Operating experience indicates that when afterburners are used to control air blowing, the emission may provide 20 to 25% of the heat requirement but the fuel costs are still quite high.

Under certain circumstances it is possible that the operating cost for a thermal afterburner system would in reality be much lower if the fuel would still be consumed for plant energy requirements. For instance, if the asphalt plant is one that manufactures its own felt, a boiler would probably be used to provide the steam necessary for this process. However, the fuel that would be used to fire the boiler could instead be diverted to an afterburner equipped with a waste heat boiler that would supply part or all of the steam required. It is obvious that under these circumstances the fuel used in the afterburner would not represent an increase in plant operating costs. Such situations could make afterburners more attractive but this is dependent on the type of plant and other individual plant factors.

Aside from capital and operating cost considerations, thermal afterburners have additional advantages in that they can and are being used for controlling emissions from both air blowing and saturating lines. Control methods which might offer lower capital cost and/or operating cost exist but these have not been used for control of air blowing. The reason that some of these other devices have not been used, or tried, was not clear.

Catalytic afterburners were also considered in this study as a possible candidate control device. This type of afterburner employs a catalyst to increase rate of reaction. The required operating temperature is lower (427 to 538°C) so the fuel requirements, and therefore the operating costs, are lower. However, the capital costs of such units are higher than those for thermal afterburners, and our analysis of the total annualized costs for both types of afterburners indicated that they would be about equal.

Further evaluation of the catalytic afterburners indicated that the quantity of catalyst required to achieve the desired removal efficiencies

(95 to 99%) was approaching the maximum for which such units have been designed. More important considerations were that the asphalt particulates contained in the emissions could plug or foul the catalyst, and that the effluent stream would contain sulfur or other compounds that could poison the catalyst. Our discussions with manufacturers of catalytic afterburners led us to conclude that the particulate matter could very well be a serious problem and that a particulate removal device would be necessary upstream of a catalytic afterburner. Assuming that to be true, it was concluded that the catalytic afterburners probably do not have any advantage over thermal afterburners for controlling emissions from asphalt blowing or saturator lines.

HEAF

The HEAF unit has been used at several plants for control of saturator line emissions. It is basically a particulate filter consisting of a moving fiberglass mat through which the effluent passes. The system exhibits a moderately high pressure drop of about 64 cm H_2O. Because of the mechanisms involved in filtration and the properties of the emissions, it was difficult to project the control efficiency capability of this device, either by theoretical means or analysis of existing test data.

Our interpretations indicated that the HEAF might be capable of up to 99% removal efficiency when preceded by a precooling section of water sprays. Use of such sprays does add some cost, and may require treatment of liquid effluent from the precooling section. Also, the HEAF device involves the secondary problem of disposal of the used mats.

Estimates of the cost of a HEAF system indicated that the costs were higher than for ESP devices, but both were considerably lower than afterburners.

The HEAF has been used only for control of saturator emissions. It would appear that when equipped with precoolers they might also be applicable to control of air blowing. Air-blowing effluent does have a higher particulate loading which would necessitate a faster usage rate for the filter mat, but the cost involved is small in comparison with other operating cost factors for HEAF units. Other problems might occur due to the nature of the air-blowing emissions, including the possibility of rapid plugging of the mat, but none could be identified with enough certainty to reject the HEAF as a candidate device for control of air-blowing emissions.

Wet Scrubbers

Wet scrubbers have been used for control of saturating-line emissions, primarily in those plants operated by Fry Roofing Company. Very little test data were available for the wet scrubbers, but the highest reported efficiency was 86%.

Because of the lack of data, we proceeded with a theoretical analysis of the removal efficiency capability of these devices (see Appendix D). The analysis was aimed at determining the pressure drop that would be required for efficient removal (95 to 99%) of a source exhibiting the particle size distribution shown previously in Figure 3. Results of the analysis indicated that such devices are not technically feasible for the desired removal efficiencies because of the excessively high pressure drops that would be required ($> 1,000$ cm H_2O).

Some additional information and evaluation of the applicability of wet scrubbers for control of asphalt emissions by other authors was located during this study. Goldfield[5/] reported that in small-scale tests of different control devices, a packed tower wet scrubber operating at 15 cm H_2O. ΔP was not promising because it achieved only 58% removal efficiency. He also mentions that the system that included exhaust from blowing stills showed signs of excessive corrosion and may necessitate use of special materials.

Another article, published in the Oil and Gas Journal[6/] stated that aerosols (from air blowing) are highly resistant to control by wet scrubbing. Similarly, the Los Angeles Engineering Manual[7/] indicates that spray scrubbers have met with limited success on control of saturators, and even though their efficiency may be as high as 90%, the effluent may still be 50 to 100% opaque because of their low collection efficiency for small (< 1 μm) particles.

MRI has recently visited two plants that involve scrubbers on saturator emissions. One was using a scrubber preceding an ESP and the other was using a scrubber alone. From the combination unit there were no visible emissions, which was not the case for the scrubber alone.

Based on the above information, it appeared very doubtful that wet scrubbers would be capable of achieving the desired removal efficiency (95 to 99%). It was not considered worthwhile to proceed with cost estimates for these devices nor evaluate other factors, such as possible water treatment problems.

The above conclusion seems justifiable for wet scrubbers in general, but it must be pointed out that the scrubber systems employed by Fry Roofing involve use of a permanganate scrubbing solution. This solution is a strong oxidizing agent generally used to remove organic vapor contaminants from gas streams. Use of such solutions may or may not improve particulate collection efficiency, but it is more likely that they could provide for removal of certain organic vapors, such as odors and possibly POMs. It is possible that weak permanganate solutions could also be used as the precooling medium upstream of a particulate removal device (HEAF or ESP). (Further testing of such permanganate scrubber units may be of interest.)

Electrostatic Precipitators

ESPs have been used to control saturator emissions. One such device that has been utilized at several plants is a two-stage dry ESP termed the "Smog Hog."™ A description of this device and ESPs in general is contained in Appendix E.

"Smog Hogs"™ are equipped with a mechanical prefilter to remove larger particles (> 10 μm) and minimize carry-over of water droplets into the ESP. They also are equipped with a similar afterfilter (presumably to collect particles that may be exhausted due to reentrainment).

The "Smog Hog"™ manufacturer indicates that for proper operation inlet air must be lower than 60° C. A premist or water spray systems is normally included for this purpose as well as to extend the required maintenance cycle. Tar-like buildup on collector plates requires cleanout or detergent washing at periodic intervals. The manufacturer did not believe the dry ESP units were suitable for control of air blowing because of the higher grain loading (i.e., > 2.3 g/Nm^3).

ESPs can be very efficient for removal of fine particles (< 2 μm) and the theoretical analysis carried out by MRI verified that they should be capable of 95 to 99% removal of particulates. For high efficiency removal of total hydrocarbon emissions it was assumed that this could be accomplished if the ESP were preceded by water spray precoolers. Some plants already employ precoolers upstream of an ESP or HEAF.

Economic analysis of the ESPs indicated that their costs would be somewhat lower than HEAF units. The ESPs also have the advantage of lower pressure drop and consequently, lower energy requirements. However, the dry ESPs are subject to some operating problems due to fouling of the electrodes and collection surfaces with asphalt. It is commonly required that they be shut down and washed out with water or detergent on a periodic basis.

It has been indicated to MRI that the problem of fouling in ESPs probably accounts for the fact that they have not been used for control of air-blowing emissions where the grain loading is higher and the emissions may be of a more tar-like nature. An alternate approach could be a wet ESP for control of such emission sources. Wet ESPs have not been tried on either source to our knowledge, but in other industries they have been used succesfully for control of sources having similar characteristics. The cost of wet ESPs is somewhat higher than the dry type, but their possible advantages appear to justify further investigation of their applicability.

RECOMMENDATIONS

The technical and economic evaluation of candidate control devices was used as the basis for specific recommendations for further research and development efforts. The objective of these efforts would be to provide the capability to reduce total hydrocarbon emissions by 99% from air blowing and saturating lines. Some of these recommendations are founded on unproven assumptions, as discussed earlier. It is important that the following recommendations should be reexamined using results of the ongoing EPA test program when they become available. The recommendations are discussed and presented below. These recommendations and their suggested priority are also summarized in Table 7.

PRIORITY I

It was found in this study that there were little actual data available from which one could ascertain that various control devices are capable of 95 or 99% particulate removal efficiency for emissions from air blowing and saturating lines. Likewise, there were even less data relative to total HC removal efficiency (i.e., percent of the hydrocarbons that are in gaseous form).

Because a current EPA program is directed to testing of the subject control devices, and does include some determination of gaseous hydrocarbons, it is recommended that these results be compiled and evaluated as soon as they are available. Specifically, they should be analyzed in an attempt to ascertain the total HC removal efficiency of afterburners on air blowing and saturator emissions, and total HC removal efficiency of HEAF and ESP units on saturators with notation of inlet temperature and whether the units were or were not equipped with precoolers.

If this analysis shows that the air-blowing emissions still contain a significant amount of gaseous hydrocarbons at the sampling (filter) temperature of 38°C (e.g., > 1%) it would have to be concluded that no particulate control device could achieve 99% removal of total HC on air-blowing emissions. A similar situation would be true if the saturator

Table 7. SUMMARY OF RECOMMENDATIONS

Priority I

A. Evaluate results of current EPA test program, as soon as they become available, to assess percent of hydrocarbons that exist as gases at 38°C.

Use this assessment to determine if Priority II recommendations should be undertaken.

Priority II

A. Conduct additional tests, as may be necessary, to characterize both emission sources for specification and design of control devices. This testing may include the following:

1. Determine particle size distributions (especially air-blowing emissions).
2. Measure *in situ* resistivity of particulate matter.
3. Use EPA test train, with temperature control, to determine percent gaseous HC as a function of temperature.

Priority III

A. Obtain and install a pilot scale ($\simeq$ 30 m^3/min) HEAF and wet ESP (with precooling section) on a sidestream drawoff from an air-blowing operation. Test both devices to determine total HC removal efficiency and assess possible operating problems.

If results of the above tests are favorable, proceed with full scale tests of these control devices. Such tests would preferably be carried out at a location where air blowing and saturator emissions could be diverted to the test units either singularly or in combination.

Priority IV (Optional)

A. Perform experiments to determine efficiency of gaseous HC removal via permanganate scrubbing. Tests could be conducted at an operating $KMnO_4$ scrubber facility or by using $KMnO_4$ solution as the precooling medium in Priority III activity.

emissions are more than 1% gaseous HC at 38°C. In this case, the Priorities II and III recommendations should be reevaluated.

Conversely, if the EPA tests show that the emissions are less than 1% gaseous HC at 38°C the Priorities II and III recommendations should be pursued.

It is important to note that the technical evaluation of afterburners has led us to conclude that properly designed afterburners should certainly be capable of 99% removal of total hydrocarbon emissions either from air blowing or saturators. Because of this, and considering the fact that afterburners are presently being used on both sources, we believe their applicability has been sufficiently demonstrated. No further research and development has been recommended for afterburners. If evaluation of the EPA test program should cast doubt on their capability for 99% removal, some further R&D work may be needed.

PRIORITY II

Priority II recommendations center on characterization of emissions, primarily to permit optimum design of control equipment especially as it may be needed for the pilot-scale devices recommended under Priority III. It is recognized that some of the necessary design information should be available from the current EPA test program. However, our familiarity with that program indicates that some additional testing will probably be required to sufficiently characterize the emissions for specification and design of control devices. Therefore, the following work has been recommended pending evaluation of the data from the current EPA test program:

1. Determine particle size distributions of emissions, especially those from air-blowing operations.

2. Measure *in situ* resistivity of particulate matter in the effluent streams.

3. For both air-blowing and saturator emissions, conduct tests to determine percent of the total hydrocarbon emissions that exist in gaseous form as a functon of temperature.

PRIORITY III

Technical evaluation of candidate control techniques indicated that HEAF and wet ESPs (equipped with precoolers) may be feasible for control of air-blowing emissions, at a significant cost reduction over afterburners. Likewise, the same should be true for saturator emissions since HEAF and dry ESPs are already used in this application and are currently being tested. It is recommended that a program be undertaken to install and test a pilot-scale HEAF and wet ESP on air-blowing emissions. The objective of this program would be to perform tests to determine removal efficiency and identify operating problems. These preliminary pilot-scale tests would be evaluated to decide if full-scale tests of either or both units are warranted.

PRIORITY IV (OPTIONAL)

Evaluations carried out in this program indicated that wet scrubbers could not reasonably achieve 99% reduction in particulate emissions. However some operating wet scrubbers utilize $KMnO_4$ scrubbing solution which might be advantageous for reducing gaseous hydrocarbon emissions. It is therefore optionally recommended that this be investigated, either by tests on an operating $KMnO_4$ scrubber at one of the asphalt production facilities that is so equipped or as an addition to the pilot-scale tests recommended under Priority III using $KMnO_4$ solution as the precooling medium.

The recommendations that resulted from this study vary in their complexity and requirements. To further delineate the work and procedures that would be involved in carrying out these recommendations, estimates have been prepared showing the cost, time and approach for each. The next section presents these estimates.

PLANNING

Final work on this study was directed to the estimation of the cost, time and approach necessary for carrying out the recommendations that have been made. These are discussed below and results have been summarized in Table 8.

PRIORITY I - EVALUATION OF RESULTS FROM CURRENT EPA TEST PROGRAM

This recommendation will require reduction and analysis of data to determine total HC removal efficiency of devices tested and determine the percent of the emissions that remain in gaseous form at 38° C. When all the data from this test program are available, it should be possible to conduct the data analysis in 1 man-month at an estimated cost of about $4,000, which includes preparation of a summary report.

PRIORITY II - CHARACTERIZATION OF EMISSIONS

This effort will be directed to characterization of emissions, to the extent it is needed for design of control devices and is not already available from other studies. This testing is expected to include, but not necessarily be limited to, those test plans presented below.

Particle Size Tests on Air-Blowing Emissions

These tests should require only about two men for 1 week at a cost estimated to be $3,100. The total time involved should be about 1 month but these tests could be carried out in conjunction with the other tests described below.

Measurement of *In Situ* Resistivity

Resistivity of the fume from asphalt saturators and air-blowing operations should be determined at least twice at two different facilities, preferably including one that utilizes a precooling system. It is estimated that this would cost about $2,000 and require one calendar month. Again, these tests could be carried out in conjunction with other tests, probably at less cost.

Table 8. SUMMARY OF ESTIMATED COSTS AND TIME REQUIREMENTS FOR RECOMMENDED RESEARCH AND DEVELOPMENT PLANS

Recommendation	Time required (months)	Estimated cost ($)
I. Evaluation of results from current EPA test program.	1	4,000
II. Characterization of emissions		
a. Particle size testing of air-blowing emissions	1	3,100
b Resistivity measurements	1	2,000
c. Tests to determine percent gaseous HC as a function of temperature	3	15,400
III. Pilot-scale testing of HEAF and wet ESP on air blowing	6	62,400
IV. Optional research		
a. Gaseous HC removal by $KMnO_4$ scrubbing	3	16,000

Tests to Determine Percent of HC Emissions that are in Gaseous Form as a Function of Temperature

The simplest method to obtain these results would be to use the sampling train being employed in the present series of EPA tests. However, this train would have to be modified to include capability for varying the temperature at the filter from 177° C down to 38° C. It would again necessitate use of the FID for determination of gaseous HCs, or perhaps special collection media in impingers after the filter. It is estimated that the sampling train could be suitably modified at a cost of less than $1,000 during the 1-month period required for site arrangements and sampling preparations.

Actual field tests at each site (one air blowing and one saturator) would require four men for 1 week at a cost of $6,200, for a total of $12,400. Compilation and evaluation of the data in report form would require another 2 man-weeks at a cost of about $2,000 but the calendar time required would probably be 1-1/2 months. Therefore, the total cost is estimated to be $15,400 and would require about three calendar months.

PRIORITY III - PILOT SCALE TESTING OF HEAF AND WET ESP ON AIR BLOWING

This is the major recommendation of the study, and requires the most effort. It will require procurement of the pilot scale test devices, arrangement for their installation at an operating plant with modifications necessary and utility hookups, testing of the devices, and reduction and evaluation of data obtained.

Specification and procurement of the devices can be carried out during the same period that arrangements are being made for their installation. We estimate that this will require 2 man-months over a 3-month period, at a cost of $7,600.

Pilot-scale tests should be conducted with units designed for flow rates of about 30 m^3/min (or more). Conversations with HEAF and wet ESP manufacturers verified that such units are available. The HEAF unit can be purchased for close to $5,000 but apparently this size unit cannot be rented or leased. Wet ESP units of this size are available for lease, but at a cost of $5,000/month. Based on these figures we estimate that total cost including auxiliaries and installation, would probably be a minimum of $10,000 each. If water treatment facilities are necessary for the short-term use of these test units, the cost will be higher. Assuming that this will not be required, total cost for both units will be $20,000.

After the units are operational, they should be operated at least 8 hr/day over a 2-week period for shakedown and adjustment and for identification of possible operating problems. This can probably be accomplished with two men for 2 weeks (1 man-month, \$5,800). Following that, each unit should be tested over a 1-week period (a minimum of five tests) which will require a test crew of eight men at a cost of approximately \$12,500 or \$25,000 for testing both units.

Once the pilot-scale tests have been completed it will probably require at least 1 month to obtain all of the laboratory test results. Evaluation of these data and report preparation can probably be carried out by the project leader in 1 man-month at a cost of about \$4,000.

In summary, the pilot-scale testing of a HEAF and wet ESP on air-blowing emissions can probably be done in a 6-month period at a cost estimated to be \$62,400.

PRIORITY IV - OPTIONAL RESEARCH

Optional testing of $KMnO_4$ scrubbing to determine efficiency of gaseous hydrocarbon removal might be carried out at one of the asphalt plants where this system is being used or it could be investigated as an addition to the pilot-scale tests recommended under Priority III. For the purpose of this report, it has been assumed that tests would be carried out at one of the existing installations.

Actual tests of one $KMnO_4$ scrubber installation would require an eight man test crew for 1 week at a cost of about \$12,500. However, it will also be necessary to allow 1 man-month for making test arrangements, observing field tests, and evaluating data including report preparation. Therefore, the total cost is estimated to be \$16,000 and will require about three calendar months, allowing for lag in obtaining laboratory data.

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APPENDIX A

LIST OF ASPHALT ROOFING PLANTS AND EMISSION CONTROL DEVICES

LIST OF PLANTS[a] ASPHALT ROOFING MANUFACTURERS AND EMISSION CONTROL DEVICES UTILIZED

Name and Address	Plant Location	Saturator[b] Control (type)	Blower[b] Control (type)
Allied Material Corporation Stroud, Oklahoma	Stroud, Oklahoma	AB	AB
	Albuquerque, New Mexico		
Artic Roofings, Inc. Edge Moor Wilmington, Delaware 19809	Edge Moor, Delaware	AB	AB
Atlas Roofing Manufacturing Company, Inc. P.O. Box 1606 Meridian, Mississippi	Meridian, Mississippi	HEAF	
Bear Brand Roofing, Inc. P.O. Box 206 Bearden, Arkansas	Bearden, Arkansas	AB	
Big Chief Roofing Company P.O. Box 980 Ardmore, Oklahoma	Ardmore, Oklahoma		
Bird and Sons, Inc. East Walpole, Massachusetts	Charleston, South Carolina	AB	
	Martinez, California		
	Norwood, Massachusetts		
	Perth Amboy, New Jersey		
	Portland, Oregon	ESP	N/A
	Shreveport, Louisiana	HEAF	
	Wilmington, California	AB	N/A
Carey, Philip Manufacturing Company Lockland Cincinnati, Ohio 45215 (now part of Celotex)	Houston, Texas	AB	
	Lockland, Cincinnati, Ohio	SH	AB
	Memphis, Tennessee	SH	
	Perth Amboy, New Jersey	AB	
	Wilmington, Illinois	HEAF	
The Celotex Corporation 1500 North Dale Mabry Tampa, Florida 33607	Birmingham, Alabama	SH	
	Camden, Arkansas	-	
	Chester, West Virginia	NONE	
	Chicago, Illinois	HEAF	
	Los Angeles, California	HEAF	N/A
	Philadelphia, Pennsylvania	HEAF	
	San Antonio, Texas	HEAF	
	Goldsboro, North Carolina	AB	AB
Certain-teed Products Corporation Valley Forge, Pennsylvania 19481	Avery, Ohio	AB	N/A
	Chicago Heights, Illinois	AB	AB
	Kansas City, Missouri	AB	AB
	Miller (Dallas), Texas	AB	
	Port Wentworth, Georgia	AB	
	Richmond, California	AB	N/A
	Tacoma, Washington	AB	N/A
	York, Pennsylvania	AB	
	Minneapolis, Minnesota		

Name and Address	Plant Location	Saturator[b] Control (type)	Blower[b] Control (type)
Congoleum-Nairn, Inc. Cedarhurst, Maryland	Cedarhurst, Maryland	HEAF	N/A
Consolidated Fiberglass Products, Inc.	Bakersfield, California	HEAF	N/A
Delta Roofing Mills, Inc. P.O. Box 546 Slidell, Louisiana	Slidell, Louisiana		
Daingerfield Manufacturing Company	Daingerfield, Texas	NONE	N/A
Elk Roofing Company Stephens, Arkansas	Stephens, Arkansas	SH	
The Flintkote Company 400 Westchester Avenue White Plains, New York	Chicago Heights, Illinois		
	Ennis, Texas		
	Los Angeles, California	HEAF	AB
	Portland, Oregon	ESP	
Lloyd A. Fry Roofing Company 5818 Archer Road Summit, Illinois 60501	Atlanta, Georgia	NONE	
	Brookville, Indiana	WS	
	Compton, California	ESP	
	Denver, Colorado	NONE	
	Detroit, Michigan	WS	
	Ft. Lauderdale, Florida	WS	
	Hazelwood, Missouri	WS	
	Houston, Texas	AB	
	Irving, Texas	NONE	
	Jacksonville, Florida	WS	
	Kearney, New Jersey	NONE	
	Lubbock, Texas	NONE	
	Medina, Ohio	NONE	
	Memphis, Tennessee	WS	
	Minneapolis, Minnesota	WS	
	Moorehead City, North California	NONE	
	North Kansas City, Missouri	WS	
	Oklahoma City, Oklahoma	NONE	
	Portland, Oregon	AB	N/A
	San Leandro, California	AB	
	Summit, Illinois	WS	N/A
	Waltham, Massachusetts	AB	
	Woods Cross, Utah	NONE	
	Jessup, Maryland	AB	
GAF Corporation 140 West 51 Street New York, New York 10020	Baltimore, Maryland		
	Dallas, Texas		
	Denver, Colorado		
	Erie, Pennsylvania	HEAF	
	Joliet, Illinois		
	Kansas City, Missouri	AB	AB
	Millis, Massachusetts		
	Minneapolis, Minnesota		
	Mobile, Alabama		
	Mount Vernon, Indiana		
	Savannah, Georgia		
	South Bound Brook, New Jersey	AB	
	Tampa, Florida		

Name and Address Name and Address	Plant Location	Saturator[b] Control (type)	Blower[b] Control (type)
Johns-Manville Corporation at Greenwood Plaza Denver, Colorado 80217	Fort Worth, Texas	HEAF	N/A
	Los Angeles, California	HEAF	N/A
	Manville, New Jersey	HEAF	N/A
	Marrero, Louisiana	HEAF	N/A
	Pittsburg, California	HEAF	N/A
	Savannah, Georgia	HEAF	N/A
	Waukegan, Illinois	HEAF	N/A
The Logan-Long Company 6600 South Central Avenue Chicago, Illinois 60638	Chicago, Illinois		
	Franklin, Ohio		
	Tuscaloosa, Alabama		
Lunday-Thagard Oil Company 9301 Garfield Avenue South Gate, California	South Gate, California	AB	AB
Malarkey, Herbert Roofing Company 3131 North Columbia Boulevard Portland 17, Oregon	Portland, Oregon	AB	N/A
Owens-Corning Fiberglass Corporation Fiberglass Tower Toledo, Ohio 43659	Santa Clara, California		
	Kansas City, Missouri		
Royal Brand Roofing, Inc. A Subsidiary of Tamko Asphalt Products, Inc. Box 385 Phillipsburg, Kansas	Phillipsburg, Kansas	AB	AB
Southern Asphalt Roofing Corporation 2500 E. Roosevelt Road Little Rock, Arkansas (presently owned by Masonite)	Little Rock, Arkansas		
Tamko Asphalt Products, Inc. 601 North High Street Joplin, Missouri 64801	Joplin, Missouri	Cyclone (ESP)	AB
Tilo Company, Inc. Stratford, Connecticut	Stratford, Connecticut	AB	AB
United States Gypsum Company 101 South Wacker Drive Chicago, Illinois 60606	Jersey City, New Jersey	AB	N/A
	St. Paul, Minnesota	ESP	AB
	South Gate, California	ESP	N/A

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[a] This list is based on information obtained from the Asphalt Roofing Manufacturers Association as well as private communication with companies.

N/A - Not Applicable	HEAF - High Energy Air Filter
AB - Afterburner	SH - Smog Hog (modular ESP)
ESP - Electrostatic Precipitator	WS - Wet Scrubber

[b] Blanks indicate information is not available.

APPENDIX B

EVALUATION OF AFTERBURNERS FOR THE ASPHALT ROOFING INDUSTRY

OPERATING PARAMETERS AND PERFORMANCE

Thermal Afterburners

In many industrial processes, combustible gaseous and vapor fumes and particulates have been successfully controlled by thermal afterburners. Essentially, the thermal afterburner incinerates the combustible gas, vapor or particulate fumes to form the principal combustion products of carbon dioxide and water. Figure B-1 indicates the key considerations involved in successful incineration of these fumes. The three T's (temperature, turbulence, and time) are the primary considerations, as in many incineration processes. In the thermal afterburner, temperature is achieved by combustion of an auxiliary fuel to heat the incoming fume. Turbulence is achieved by injection nozzles and flow-diverting baffles, and time is obtained by providing adequate space for retention of the fumes for the desired time. Detailed discussions of these afterburner designs and operating considerations are included in other reports.[1,2]

Operating Conditions - Following years of practical experience, a retention time of at least 0.3 to 0.5 sec is desired in afterburner designs.[1] Temperature requirements to achieve desired levels of control (or removal) efficiency have also been determined for gases, vapors, and odors.[1-3] The temperatures and ranges versus control efficiency for (a) odors, (b) hydrocarbons (HC) and carbon monoxide (CO), and (c) methane are presented in Figure B-2. Based on these temperature ranges, the minimum design temperatures to assure control of HC and CO in the asphalt roofing industry should be 750°C for 90% control, 782°C for 95%, and 816°C for 99%. Note that these recommended minimum temperatures are still far below the temperatures required for incineration of dilute fumes of methane. The additional retention time required to burn a 100-µm hydrocarbon droplet has been shown to be about 0.02 sec at 760°C.[2] Since drops larger than 50 to 100 µm are easily removed in simple cyclones or knockout vessels, no special problems

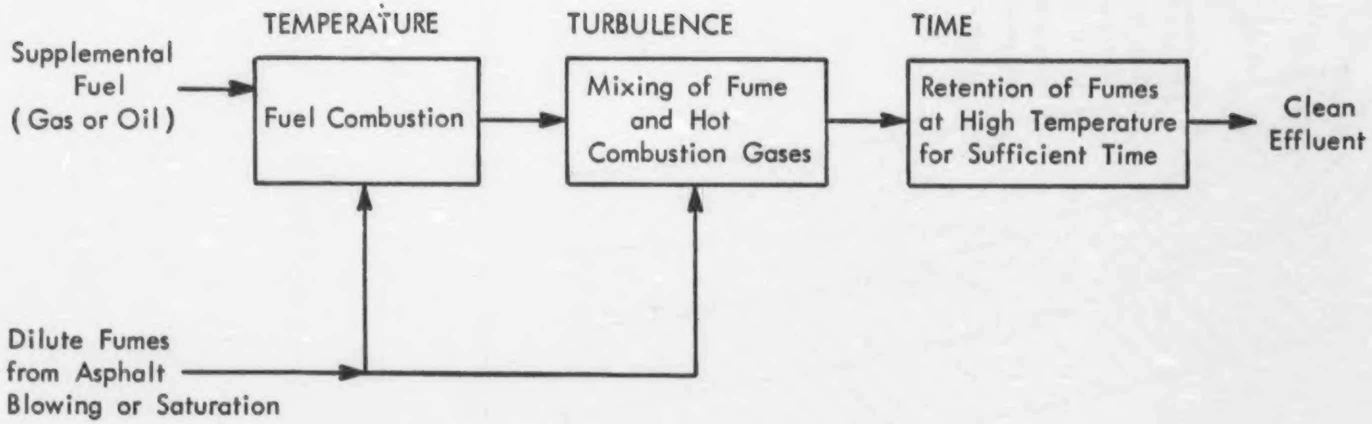

TEMPERATURE
TURBULENCE
TIME
Supplemental Fuel (Gas or Oil)
Fuel Combustion
Mixing of Fume and Hot Combustion Gases
Retention of Fumes at High Temperature for Sufficient Time
Clean Effluent
Dilute Fumes from Asphalt Blowing or Saturation

Figure B-1. Consideration for Successful Incineration of Dilute Fumes

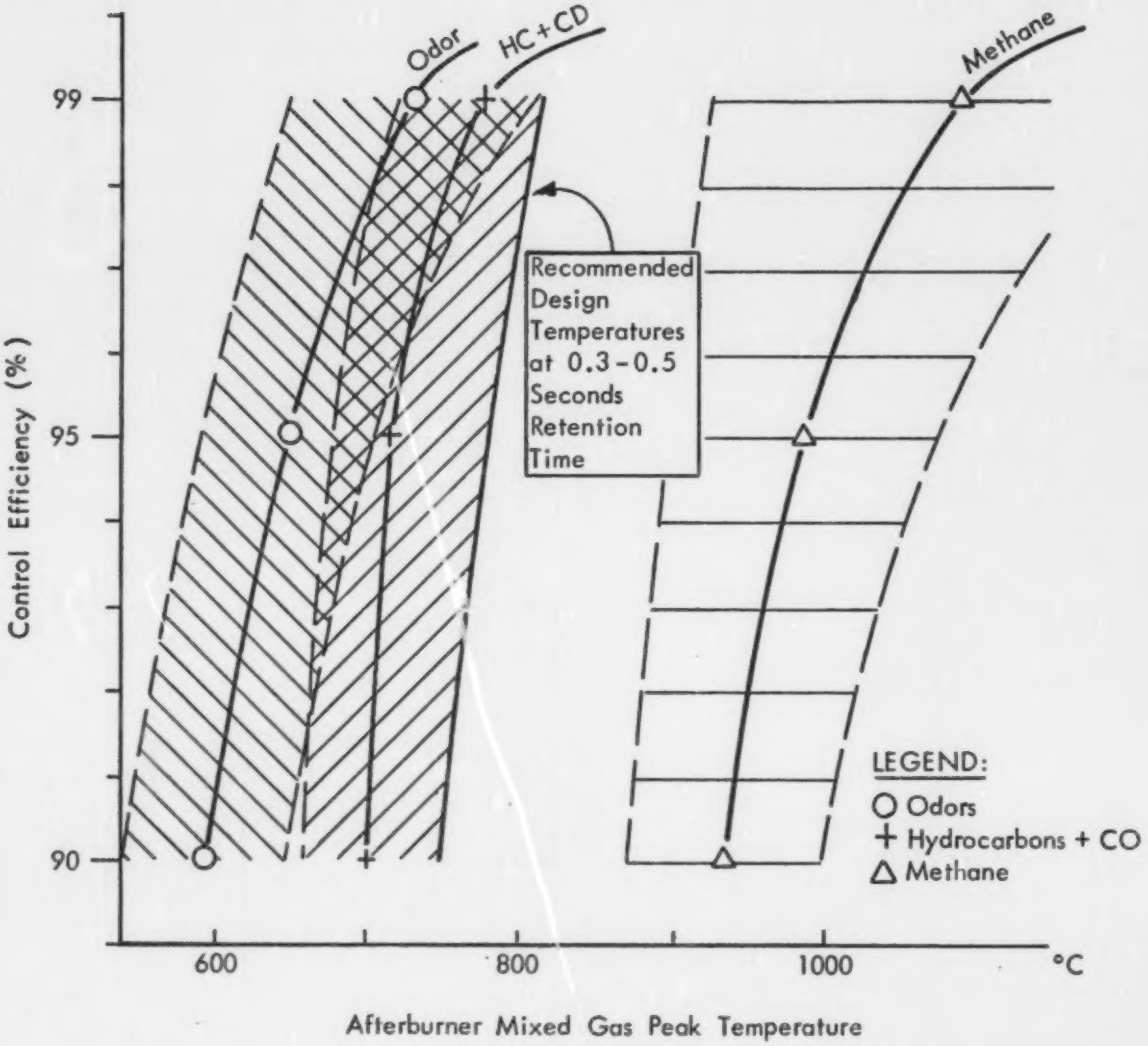


Figure B-2. Afterburner Operating Temperature Versus Removal Efficiency are expected relative to rates of pollutant destruction. Knockout vessels are routinely used in the asphalt roofing industry in flue gas lines from asphalt blowing, storage vessels, and saturators. Certain practical problems such as fouling of burners and buildup in duct work may be encountered with asphalt droplets.

User Survey - A survey of users of thermal afterburners was conducted by Shell.[2] The survey results for 214 afterburners indicated that the performance of 89% was satisfactory, with seven not yet run. Main operating problems involved safety controls, refractory linings and heat exchanger fouling or mechanical failure. However, most units were available 95 to 99% of the time so that maintenance downtime was a minor problem.

In the same survey,[2] 39% of the afterburners included heat exchangers for energy conservation. Only 66 gave an indication of hydrocarbon reduction efficiency with 62% of these respondents reporting over 95% reduction efficiency and 94% reporting achievement of over 90% reduction efficiency.

Catalytic Afterburners

Catalytic afterburners are similar to thermal afterburners in requiring a supplemental fuel source for heating the flue gas, but the catalytic afterburner also includes a catalyst bed or matrix structure to accelerate the oxidation reaction. As a result of the use of the catalyst, the catalytic afterburner can be operated at lower temperature than a thermal afterburner to achieve the same hydrocarbon reduction efficiency. This lower temperature will result in savings in fuel requirements. However, to achieve high levels of hydrocarbon reduction efficiency, above 95%, either the amount of catalyst used must be increased at a high economic cost and high pressure drop or the temperature must be increased to approach the thermal afterburner temperature. If fuel costs continue to increase at a faster rate than catalysts, the costs of catalytic afterburners with reduction efficiencies above 95% may be practicable.

Aside from the operation parameters of temperature, turbulence, and retention time, catalytic afterburners have another set of variable parameters associated with the catalyst. These catalyst parameters include volume of catalyst, volume/flow of flue gas, surface area of catalyst, porosity of catalyst, oxidation reactivity, size of catalyst pellets or interstices and type of catalyst. Some contaminants in the flue gas may also react with the catalyst in irreversible reactions (called "poisoning"). Other contaminants can clog the catalyst pores. As a result, the reduction efficiency of catalytic afterburners is expected to decrease with age but with proper design, the catalyst bed in the catalytic afterburner can be sized for 10 to 15 years of operation without replacement.

Operating Conditions - For most hydrocarbons and catalysts, the minimum temperatures required for 90% conversion with solvent concentrations of 10% LEL have been reported as 249 to 349°C.[2] These are minimum temperatures for a new catalyst with no aging or poisoning. Because of aging and poisoning, the operating temperature should probably be at 370 to 427°C to assure 90% conversion. Figure B-3 shows typical performance versus temperature curves. For this example, the temperatures required are 482°C to achieve 90% conversion of hydrocarbon and about 650°C to achieve 95% conversion. At lower temperatures than the 750°C for 90% and 782°C for 95% conversions required for thermal afterburners, a savings of 42 and 23%, respectively, in heat energy and supplemental fuel requirements is possible. However, 99% conversion might not be achieved by this catalytic afterburner even at the 816°C thermal afterburner temperature. The 99% conversion for the example in Figure B-3 would require additional catalyst volume resulting in increased cost and increased pressure drop through the bed or matrix.

User Survey - In a 1972 survey of users of catalytic afterburners only a small response with 24 units being reported was obtained.[2] Of these 24 units, 25% included heat exchangers. Only 30% of the units were reported to be satisfactory. The major maintenance problem was catalyst poisoning reported in 71%. Reduction efficiency was only reported for one unit at 90%.

AFTERBURNERS IN USE IN THE ASPHALT ROOFING INDUSTRY

A total of 76 asphalt roofing plants have been identified from information obtained from the Asphalt Roofing Manufacturers Association and private communication with companies.[4] Up to 82% of these plants purchase blown asphalt from refineries and do not have asphalt blowing operations. Of the 13 plants identified which have blowing operations, all 13 use thermal afterburners. For the saturator operations, 28 of 76 plants or 37% use thermal afterburners and 9 of 76 have no emission control devices at all. No catalytic afterburners were reported in use. The opinion was expressed that the asphalt droplets in these roofing plant emissions would cause rapid fouling of the catalyst.

A detailed survey of 33 roofing plants showed only 13 with asphalt blowing operations.[4] The results of this survey also indicated the following information on afterburners in use in the industry:

Flow Rates
Range: 85 to 1,416 Nm^3/min
Mean: about 283 Nm^3/min

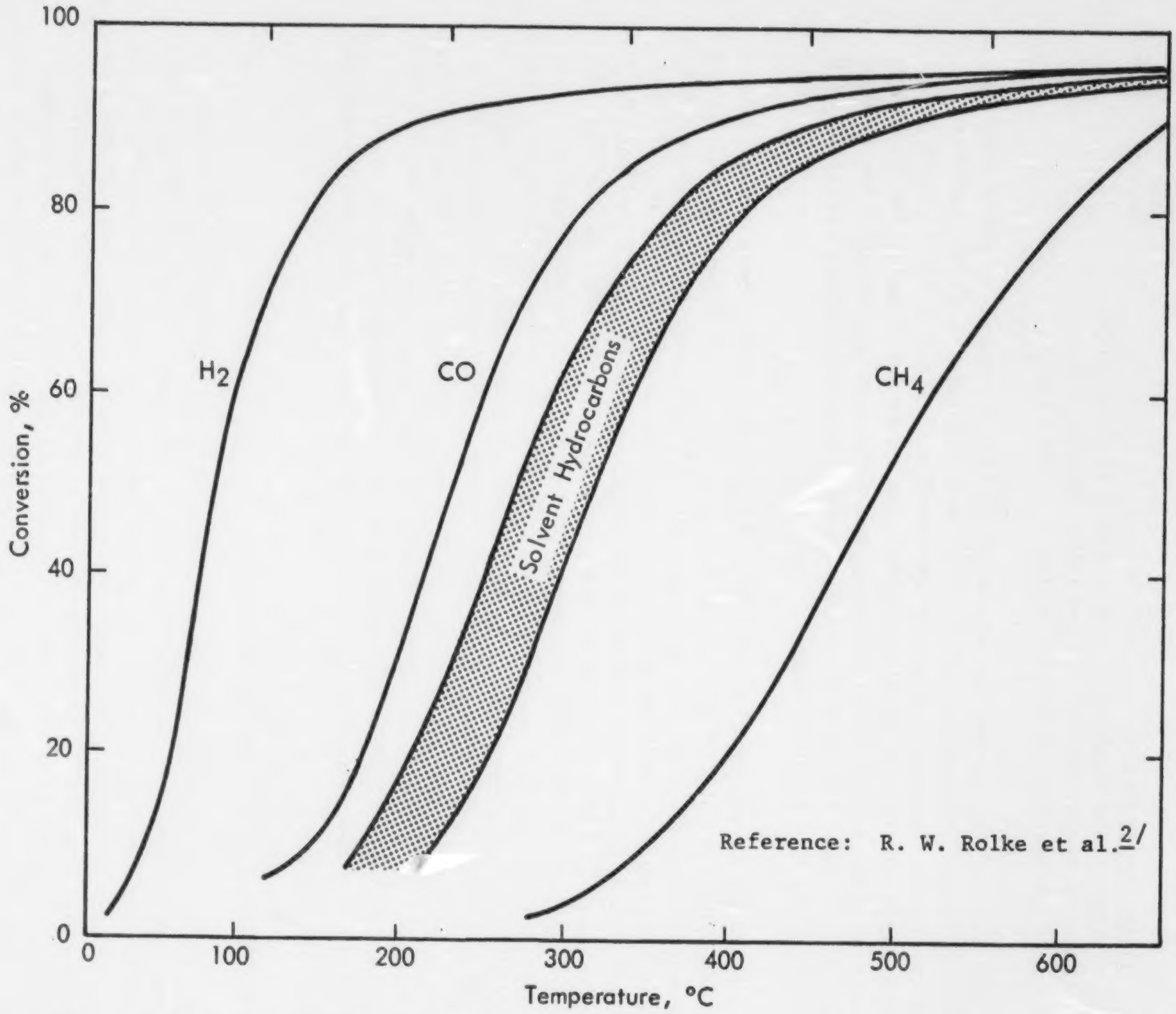


Figure B-3. Typical Temperature-Performance Curves for Various Molecular Species Being Oxidized Over Pt/Al_2O_3 Catalysts

Saturator Emissions
Average grain loading: 0.80 g/Nm^3 (0.64 to 1.08)
Average temperature: ~ 68°C (60 to 74)
Average moisture content: ~ 3% (1.5 to 3.8)

Blower Emissions
Average grain loading: 8.4 g/Nm^3 (0.7 to 25.6)
Average temperature: ~ 121°C (94 to 153)
Average moisture content: ~ 16% (5.1 to 19.5)

An analysis of the operation schedules of the 13 plants weighted with respect to plant production in tons per year indicated that the weighted average annual operating time for saturators is about 5,480 hr/year and for asphalt blowing is about 2,080 hr/year (only two samples for blowing). Note that some plants combine blower and saturator gas streams for treatment in a common afterburner which can then have an average operating time in excess of the 5,480 hr/year.

Afterburners in use in the asphalt roofing industry are operated at temperatures from 538 to 1090°C.[2/] Data from another survey indicated that afterburners are operated at 638°C up to 816°C.[4/] Test results in a Los Angeles plant indicate a reduction efficiency of 90.4% of organics by Rule 52 and of 88% of total organics for an afterburner operating at 250 Nm^3/min (no indication of afterburner operating temperature is given). In another afterburner test in Illinois at about 708 Nm^3/min with natural gas and with No. 6 fuel oil as supplemental fuels, the afterburner met all state requirements for average particulate (0.038 g/Nm^3 measured for gas fuel, 0.088 g/Nm^3 for oil fuel) for sulfur dioxide (7.91 ppm for gas, 14.64 ppm for oil) and total hydrocarbons (121 to 112 ppm). Nitrogen oxide emissions were also measured at 16.3 ppm. This afterburner was reported to be designed to operate at 704 to 760°C, but no data on input emissions were measured to evaluate the reduction efficiency since the existing exhaust emission standard was met.

Afterburner Fuel/Energy Requirements

Fuel/Energy Requirements - Thermal and catalytic afterburners both require supplemental fuel to heat the flue gas to the desired combustion or oxidation temperature. The amount of energy required is directly related to the mass flow rate of the flue gas, the specific heat of the flue gas and the temperature difference from afterburner inlet to the desired combustion temperature. For flue gas with 16% moisture, the heat energy requirement as a function of flue gas volume flow rate and peak afterburner mixed gas temperature is presented in Figure B-4. For use in asphalt blowing, the inlet temperature has been selected at 121°C. The same figure can also be used for an approximation of the requirements for saturator flue gas if 35°C is added to the peak mixed gas temperature (to correct for an inlet

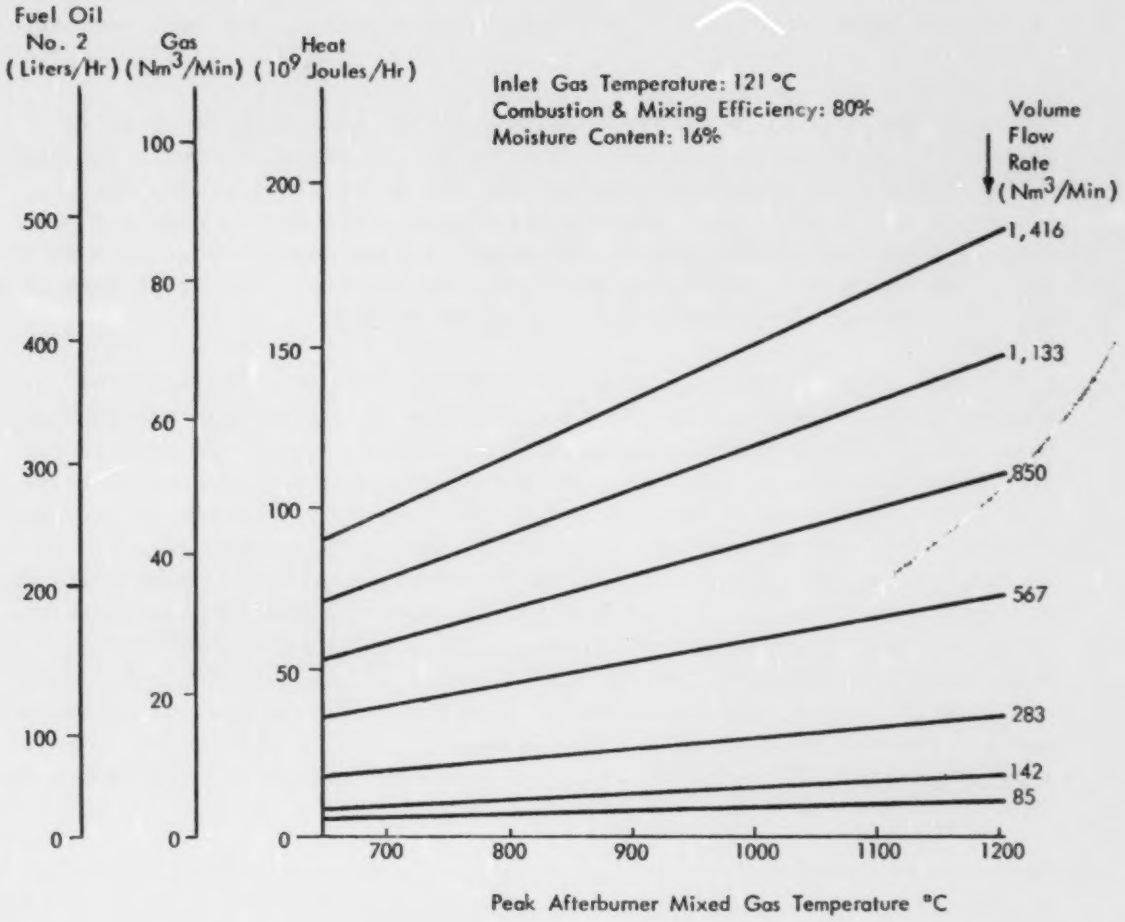


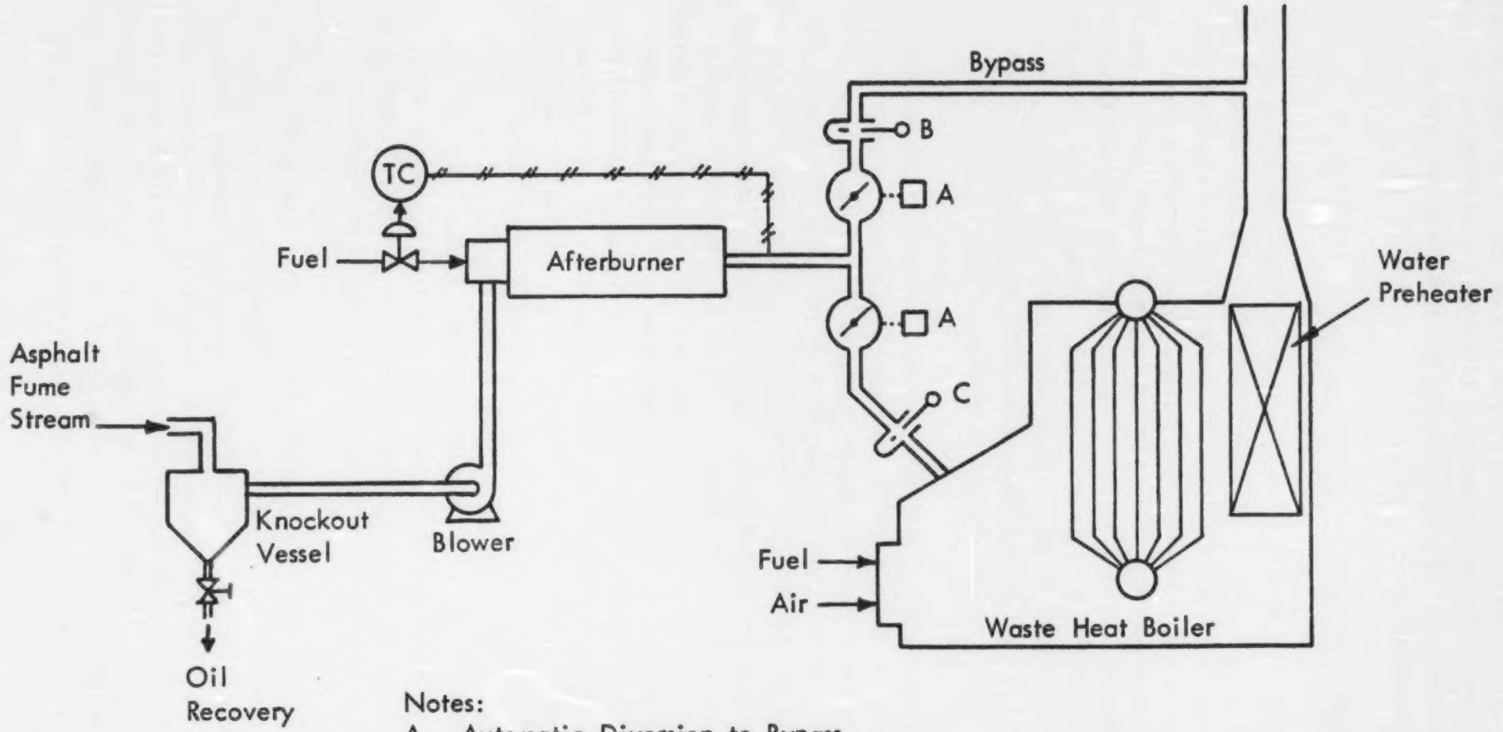
Figure B-4. Thermal Afterburner Heat and Fuel Requirements Versus Temperature and Volume Flow Rate of 68°C). The requirements for natural gas at 35.3 x 10^6 joules/Nm^3 and for No. 2 fuel oil at 38.2 x 10^6 joules/liter are also presented in Figure B-4. For example, an afterburner operated at 816°C (~ 99% HC reduction efficiency) and 283 Nm^3/min would require about 22 x 10^9 joules/hr of energy, which represents about 708 m^3/hr of natural gas or about 75 liters/hr of No. 2 fuel oil. The combustion and mixing efficiency for the heated gases is assumed to be about 80% to make allowance for the added fuel requirements.

The pressure drop in an afterburner is usually around 2.5 cm of water. Since this pressure drop is small and the fan is required anyway for asphalt blowing and saturator venting, the fan power requirements for the afterburner is negligible. However, if a heat exchanger is used for energy recovery and conservation, the pressure drop may increase to 5 to 10 cm of water and some added fan power will be required, but still much less than is required for a HEAF filter at 66 cm of H_2O.

Heat/Recovery/Energy Conservation - In the last 2 years the costs of fuel have more than doubled, and adequate supplies of natural gas and fuel oil have become hard to find. As a result, some form of heat recovery is almost mandatory for afterburners. Heat energy has been recovered in three ways in the asphalt roofing industry: (a) by use of a preheater heat exchanger using the exhaust hot gas to heat the incoming flue gas, (b) by use of a heat exchanger using the hot exhaust gas to heat thermal liquids or asphalt flux, or (c) by use of the hot exhaust gases in an auxiliary steam boiler. Afterburner heat exchangers currently on the market can achieve 67.5 to 80% heat recovery, or more if additional paths or modules are used.[3/] For a known heat recovery percent, the energy and fuel requirements presented in Figure B-4 will decrease proportionately. For example, a 50% recovery heat exchanger reduces the energy and fuel requirements by 50%.

The catalytic afterburner, by operating at a lower temperature than the thermal afterburner will require less energy and fuel with savings of about 42% for 90% hydrocarbon conversion efficiency and about 23% for 95% hydrocarbon conversion efficiency. Many catalytic afterburners also include heat exchangers for heat recovery.

Problems with certain types of heat exchangers and with catalytic afterburners can be anticipated in applications for the asphalt roofing industry because of potential fouling of surfaces with coatings from the asphalt droplets. This potential fouling problem might be avoided by using the hot exhaust gases in a gas-liquid heat exchanger to heat a thermal liquid or the asphalt flux or in a steam boiler to generate steam. A steam boiler installation similar to that used at GAF in Kansas City is indicated in Figure B-5. Here, the flue gases from the asphalt blowing, heated storage tanks and saturators flow through two knockout vessels and two fans at 425 Nm^3/min each into the thermal afterburner. The exhaust gases from the


Bypass
B
TC
A
Fuel
Afterburner
A
Water
Preheater
Asphalt
Fume
Stream
C
Knockout
Vessel
Blower
Fuel
Air
Waste Heat Boiler
Oil
Recovery

Notes:

A Automatic Diversion to Bypass
1. When Stream Pressure/Temp. Excessive and Boiler Fuel Cut to Minimum (Using Dual-Range Controller on Boiler Fuel).
2. Upon Loss of Boiler Feed Water.
3. Upon Loss of Boiler Flame.
4. (Closure of Both) Upon Shutdown of Afterburner.

C Blind When Boiler Not in Service

B, C Blinds When Afterburner Not in Service.

Figure B-5. Afterburner with Recovery Boiler afterburner are then vented through an auxiliary steam boiler to the stack. The boiler can also be bypassed for operations when the afterburner is not in use. Supplemental fuel and air is available to the boiler to maintain the required steam output rate.

Thermal Afterburner Economics

A large amount of economic information on the capital and operating costs of thermal afterburners is available from surveys in two major environmental studies.[2,5] The capital cost data from both studies has been upgraded to 1975 estimated costs by using the ratio of construction cost indexes as a corrective multiplier. The updated capital costs for thermal afterburners for both studies have been combined to obtain the estimated 1975 capital costs as presented in Figure B-6. The capital costs in Figure B-6 are presented as a function of gas volume flow rate and temperature rise. The capital costs include an allowance of 100% for installation costs based on current estimates of relative costs of installation.[2]

Information on the operating costs of afterburners and estimates of the annualized costs of capital, depreciation and operation have also been presented in the previous studies.[2,5] In both studies, the cost of fuel is the major operating and annualized cost for the afterburner. The cost of fuel versus peak afterburner mixed gas temperature is presented for asphalt blowing and saturation in Figure B-7. The fuel costs are presented for No. 2 fuel oil at 10¢/liter and for natural gas at $\$1.22/10^9$ joules. These fuel costs are for February 1975 from the U.S. Department of Labor,[6] and are more than double the $47¢/10^9$ and $57¢/10^9$ joules for natural gas used in previous studies. Because of this drastic increase in fuel costs, which is expected to continue to increase, the future use of afterburners may become economically unfeasible. Also, these increased fuel costs leave little doubt as to the economic advisability of spending capital to add heat recovery devices to afterburner units. In comparing the fuel costs in Figure B-7 to the capital costs in Figure B-6 for 283 Nm^3/min (or 330 actual cubic meters per minute) and 816°C peak temperature, the annual costs are about eight times the installed capital cost for No. 2 fuel oil and about four times the installed capital costs for natural gas.

An annual cost of the afterburner has been estimated from the capital costs and fuel costs by including allowances for depreciation, interest and taxes, and maintenance. The depreciation was based on straight-line depreciation for a 15-year life and maintenance was based on a yearly cost of $\$3.53/Nm^3/min$.[5] Interest and taxes were assumed at a current rate of 9% of capital costs. The annual costs for an asphalt blowing and saturator application are presented in Figure B-8. These costs are presented for typical blower and saturators operated at average temperatures and hours per year.

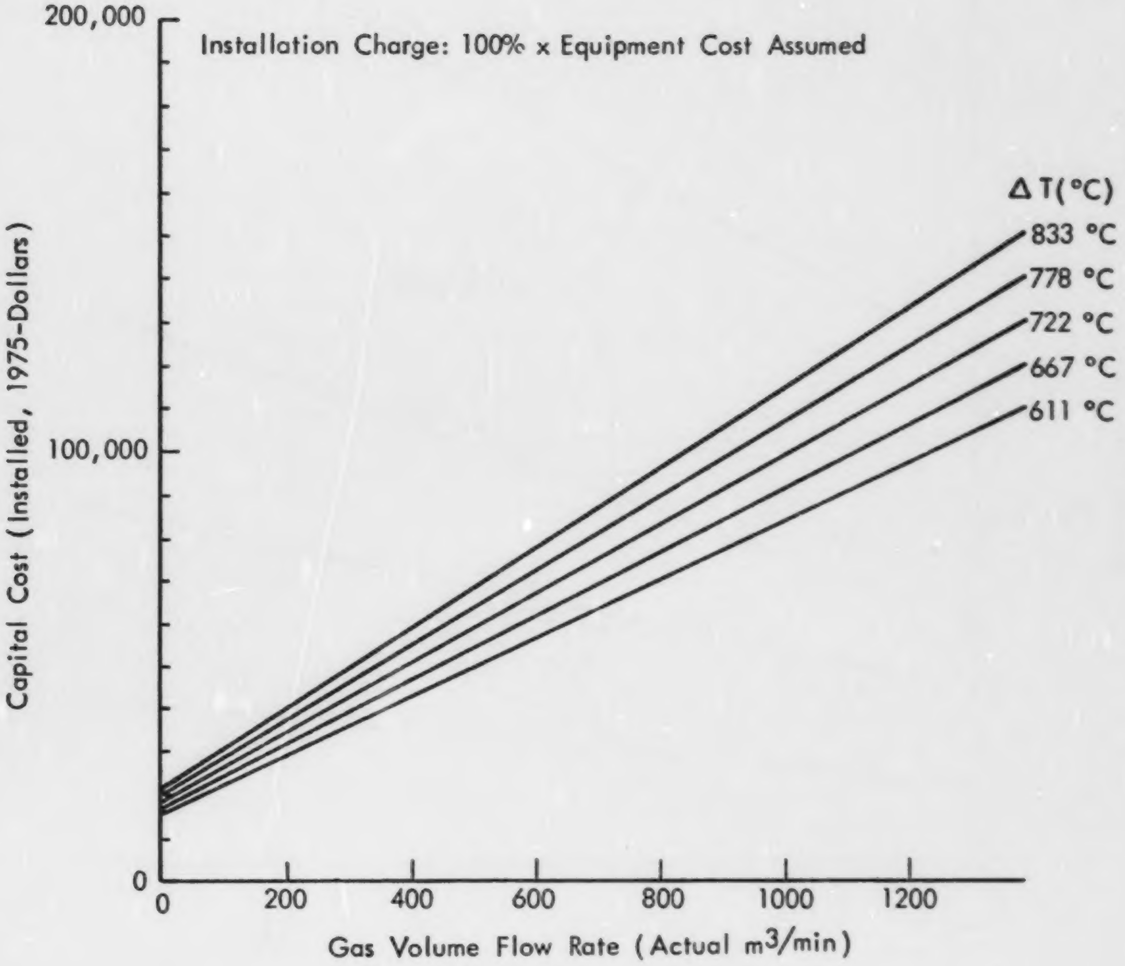


Figure B-6. Estimate Capital Costs for Installed Afterburner Versus Flow Rate and Temperature Rise

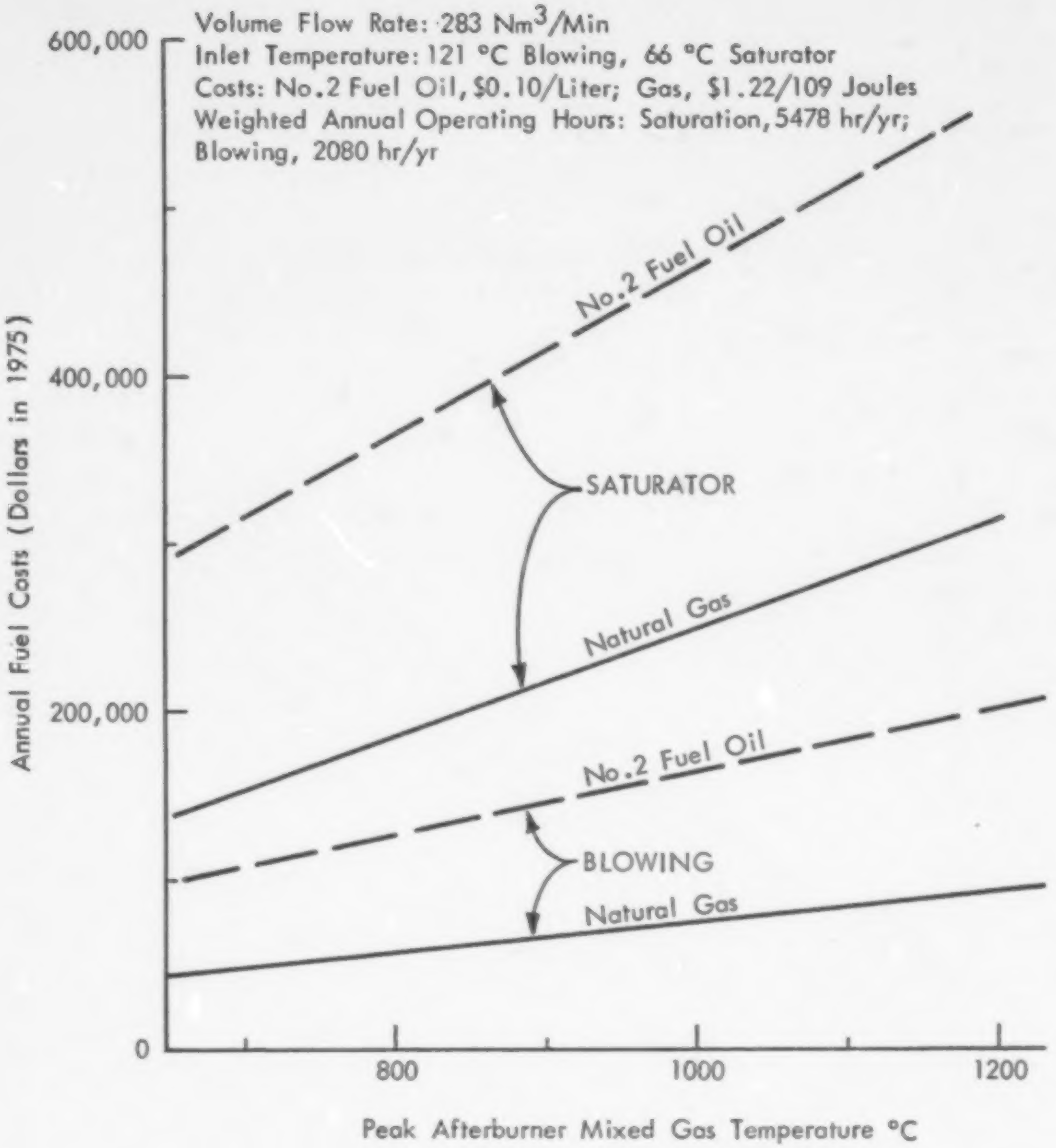


Figure B-7. Estimated Annual Fuel Costs for Thermal Afterburners Without Heat Recovery

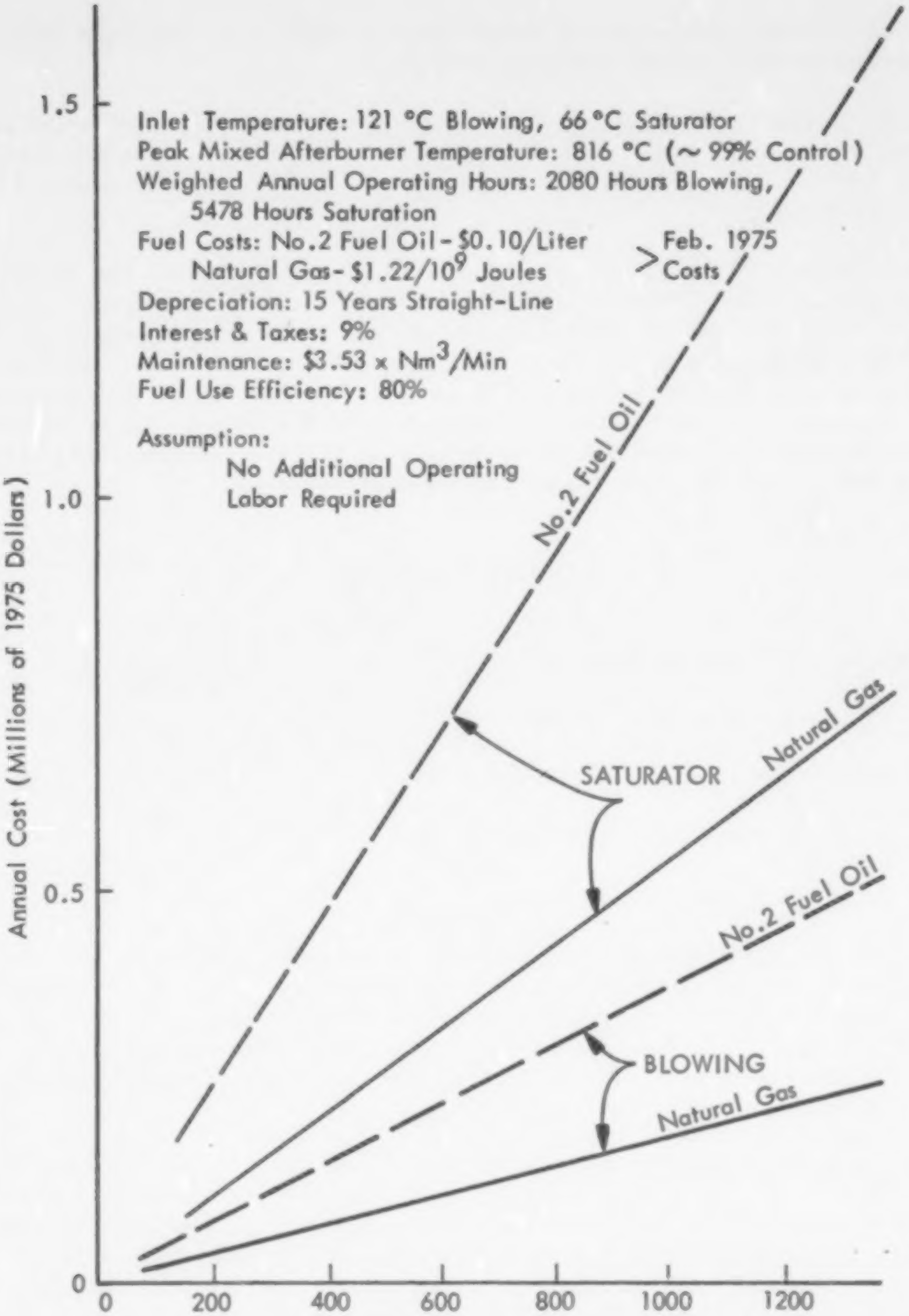


Figure B-8. Estimated Annual Costs for Thermal Afterburners Without Heat Recovery

An afterburner peak mixed gas temperature of 816°C was used since this represents about 99% HC reduction efficiency.

If the saturator and blowing flue gases are combined, the total operating time of the afterburner might be higher than the 5,478 hr/year for saturator applications, and the cost would increase proportionately (since fuel is the major cost).

From Figure B-8, note that the annual cost of an afterburner (or afterburners) for 906 m^3/min of gas volume flow rate can run as high as $1 million. This cost can be reduced by use of heat exchangers or other heat recovery methods. The capital costs will increase but the annual costs will decrease at a much higher rate. For example, the fuel costs will decrease as a direct function of the heat recovery, but the annual cost of capital will increase approximately as an inverse of the heat recovery. The resulting annual cost equation can be expressed as follows:

$$AC = Ax(1 - N) + Bx\left(\frac{1}{1 - N}\right) + C$$

where AC = annual cost,

A = fuel cost factor,

B = capital cost factor,

C = constant cost factor, and

N = heat recovery ratio.

From the equation and the cost information currently available, the cost factor C is low and cost factor A is much larger than B . Consequently, at present the most heat recovery possible up to at least 80% recovery ($N = 0.8$) results in the least annual cost. The estimated comparative costs for application of thermal afterburners to control saturator and air blowing emissions are shown in Tables B-1 and B-2.

Catalytic Afterburner Economics

A large amount of economic information on catalytic afterburners is also available from the previous surveys.[2,5] The capital costs of catalytic afterburners are comparable but tend to be slightly higher than for thermal afterburners because of the cost of the catalyst and because of the more customized application requirements. The fuel costs are less for catalytic afterburners and can result in a 43% savings in fuel requirements for 90%

Table B-1. ESTIMATE OF THERMAL AFTERBURNER COSTS FOR SATURATORS

Afterburner capacity: 565 m^3/min at 68°C inlet temperature
Operating time: 5,480 hr/year
Application: Asphalt saturator

A. 95% Hydrocarbon removal efficiency: (782°C peak mixture temperature)

Heat recovery (%)	0	50	80
Capital cost (incl. installation)	$ 62,400	$124,800	$312,000
Annual cost[a]			
Depreciation (15 years)	$ 4,160	$ 8,320	$20,800
Interest and taxes (9%)	5,620	11,230	28,080
Maintenance	2,000	3,440	4,400
	$ 11,780	$ 22,990	$ 53,280
Fuel: Natural gas ($1.22/ 10^9 joules)	$284,200	$142,100	$ 56,840
or No. 2 fuel oil ($0.10/ liter; $2.63/$10^9$ joules)	611,210	305,600	122,240
Total annual costs:			
- with natural gas	$295,980	$165,090	$110,120
- with fuel oil	$622,990	$328,590	$175,520

B. 99% Hydrocarbon removal efficiency: (816°C peak mixture temperature)

Heat recovery (%)	0	50	80
Capital cost (incl. installation)	$ 65,320	$130,640	$326,600
Annual cost[a]			
Depreciation	$ 4,360	$ 8,710	$ 21,770
Interest and taxes	5,880	11,760	29,390
Maintenance	2,000	3,440	4,400
	$ 12,240	$ 23,910	$ 55,560
Fuel: Natural gas	$297,470	$148,750	$ 59,490
or No. 2 fuel oil	639,750	319,900	127,940
Total annual costs:			
- with natural gas	$309,710	$172,660	$116,050
- with fuel oil	$651,990	$343,810	$184,500

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[a] Assuming no additional operating labor required.

Table B-2. ESTIMATE OF THERMAL AFTERBURNER COSTS FOR AIR BLOWING

Afterburner capacity: 565 m^3/min at 121°C inlet temperature
Operating time: 2,080 hr/year
Application: Asphalt air blowing

A. 95% Hydrocarbon removal efficiency: (782°C peak mixture temperature)

Heat recovery (%)	0	50	80
Capital cost	$ 58,010	$116,020	$290,060
Annual cost[a]			
Depreciation (15 years)	$ 3,870	$ 7,740	$ 19,340
Interest and taxes (9%)	5,220	10,440	26,110
Maintenance	2,000	3,440	4,400
	$ 11,900	$ 21,620	$ 49,850
Fuel: Natural gas ($1.22/ 10^9 joules	$100,290	$ 50,140	$ 20,060
or No. 2 fuel oil ($0.10/ liter)	215,680	107,840	43,140
Total annual costs:			
- with natural gas	$112,190	$ 71,760	$ 69,910
- with fuel oil	$227,580	$129,460	$ 92,990

B. 99% Hydrocarbon recovery: (816°C peak mixture temperature)

Heat recovery (%)	0	50	80
Capital cost	$ 60,730	$121,450	$303,640
Annual cost[a]			
Depreciation	$ 4,050	$ 9,100	$ 20,240
Interest and taxes	5,470	10,930	27,330
Maintenance	2,000	3,440	4,400
	$ 11,420	$ 23,470	$ 51,970
Fuel: Natural gas	$104,970	$ 52,490	$ 21,000
or No. 2 fuel oil	225,750	112,900	45,150
Total annual costs:			
- with gas	$116,390	$ 75,960	$ 72,970
- with oil	$237,170	$136,370	$ 97,120

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[a] Assuming no additional operating labor required.

hydrocarbon reduction efficiency. But, note that operation of catalytic afterburners at reduction efficiencies of 99% is doubtful based on past performance and catalyst costs, and note that none have been applied in the asphalt roofing industry.

CONCLUSIONS AND RECOMMENDATIONS

The information compiled on thermal and catalytic afterburner performance, fuel requirements, and capital and operating costs has been presented in this appendix. The available information on thermal afterburners is sufficient and enough experience has been gained in actual use in the asphalt roofing industry. Follow-up information is needed on actual test evaluations in asphalt roofing plants to verify the recommended peak mixed gas operating temperature versus total hydrocarbon reduction efficiency.

The catalytic afterburner has not had use in asphalt roofing plants and has a poor user history. Follow-up for the catalytic afterburner may require (a) extensive tests of the possibilities of catalyst poisoning and fouling with asphalt droplets at asphalt roofing plant operating conditions and (b) evaluation tests to verify performance at 95 to 99% reduction efficiency with the catalyst after aging.

REFERENCES FOR APPENDIX B

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6. Retail Prices and Indexes for Fuels and Utilities, U.S. Department of Labor, Bureau of Labor Statistics, February 1975.

APPENDIX C

EVALUATION OF THE PERFORMANCE OF HEAF (HIGH ENERGY AIR FILTRATION) SYSTEM FOR CONTROLLING EMISSIONS FROM ASPHALT SATURATORS/BLOWERS

INTRODUCTION

Control systems presently used in controlling asphalt saturator emissions may be listed as afterburners (or fume incinerators), high energy air filters (HEAFs), electrostatic precipitators (ESPs), and wet scrubbers. An MRI survey of 76 saturators indicates that 28 are controlled with afterburners, 18 with HEAFs, 10 with ESPs, and 9 with wet scrubbers. The remaining 11 are uncontrolled. Because of increasing fuel costs, afterburners are being replaced either by HEAF units or ESPs.* ESP units usually require more maintenance because of problems encountered in handling sticky asphalt aerosols; therefore, HEAF units are being selected more often than ESPs. Wet scrubbers currently used in the industry are all owned by one roofing company and have not been utilized by other companies within the industry. Also, from the available data on one of these wet scrubbers, this type of control system does not appear to be a potential candidate for best technology because of the low removal efficiency (≈ 70%). Of these four systems, only afterburners have been used for controlling emissions from the asphalt blowing operation.

DESCRIPTION OF A HEAF DEVICE

The operation of a HEAF unit is shown in Figure C-1. Solid and liquid particulate matter to be removed from the process exhaust stream are passed through a slowly moving blanket of glass fiber material which is disposed of after use. The thickness and number of fibers in the pad provide a high degree of impingement resulting in high particulate collection efficiencies on the order of 95 to 98%.[1] After passing through the glass fiber mat, the exhaust stream goes through a mist eliminator to capture any entrained matter.

Glass fiber mats bonded with a phenolformaldehyde resin are normally used but other fiber materials can also be employed. The filtering mat can vary between 0.08 to 3.8 cm in thickness with densities between 6.4 and 128 kg/m^3.[1] Usually, they are 2.54 cm thick. The fiber diameter is reported to vary from 1 to 13 µm.[2] Filtering velocities cited in Ref. 1 were generally in the range of 76 to 213 m/min with pressure drops between 15 and 65 cm of water. However, as discussed later, face velocities of 457 to 518 m/min are recommended by the manufacturer.

The filtering pad is in roll form and as the pad becomes exposed to the gas stream and loaded with particulate, the roll advances to expose a clean portion. The pad can either be manually advanced or automatically advanced at a predetermined rate. Automatic advancement is usually employed and the advancement can be triggered either by a timer or by a solenoid

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* Includes the modular multistage units (e.g., "Smog Hog"™).

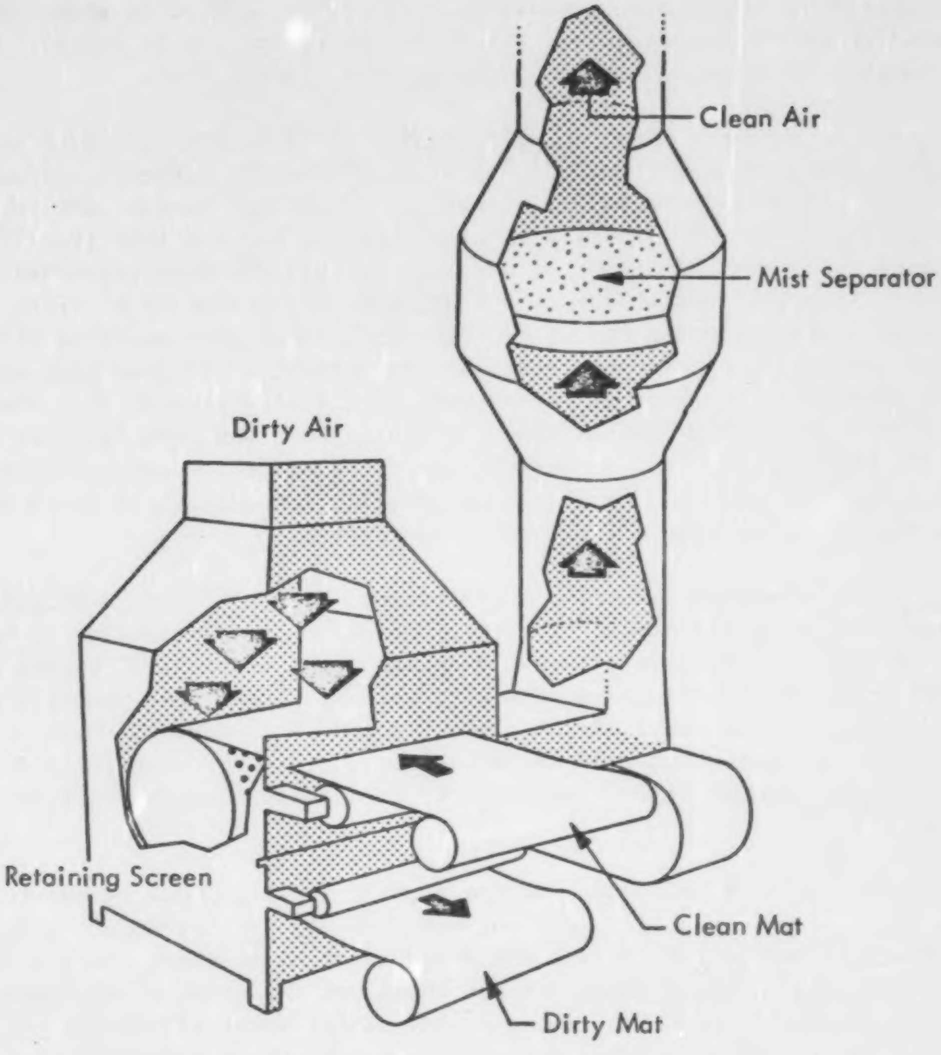
Clean Air
Mist Separator
Dirty Air
Retaining Screen
Clean Mat
Dirty Mat

Figure C-1. Operation of a HEAF unit.

when the pressure drop exceeds a prescribed limit. The mat uncoils from a spool, passes over a metal perforated drum, returns to a rewind spool and is then disposed of. The average life of the exposed portion of the mat is about 3 hr. Under worst conditions, it can be reduced to about 30 min, according to the manufacturer. A roll of the filter mat is usually 30 m in length and is available in widths of 45.7 and 121.9 cm.

In order to obtain collection efficiencies of 95 or 99% with HEAF units operating on effluent streams containing condensible material, it may be necessary to provide means for precooling of the gas stream. Cooling is not generally done by dilution with ambient air because this greatly increases the amount of air to be handled. Discussions with personnel at plants using HEAF units indicated that gases are precooled at times, usually with water sprays. One plant which had a HEAF unit equipped with a water precooling system reported that the saturator exhausts were cooled from about 67°C to about 54°C. However, it was also claimed that the plant only used the cooling system when a visible plume was seen from the HEAF stack. Although the cooling was claimed to be effective against visible emissions, no data were available to quantify its effectiveness in enhancing overall collection efficiency of the system.

It appears as though potential water pollution problems and difficulty of separating oil-water emulsions may be the reason why precooling of exhaust gas streams to HEAF inlets is not done on a routine basis to enable collection of condensible gases. The manufacturer claims that precooling will increase operating costs due to costs required for pumping H_2O. Also, cooling will increase grain loadings on the mat due to condensation and this will reduce the mat life. Therefore roofing plants tend to avoid this operation.

The application of HEAF units in the asphalt roofing industry has its pros and cons. Among the advantages, one can cite ease of operation, reduced maintenance and no fuel costs. The disadvantages, however, are its inability to control gaseous emissions and odors and the disposal problems with the used mats. In addition, water pollution may occur if exhaust gas cooling is undertaken with water sprays. Electrical power consumption may also be significant due to high horsepower blowers used in these units. Plant personnel at one facility also indicated that the unit was excessively noisy and it was necessary to install a silencer beyond the demister. However, this was not observed in the HEAF installations at other roofing plants that were surveyed.

PERFORMANCE

Based on Theory

The performance of high energy air filters can be theoretically evaluated from a knowledge of the basic mechanisms for particulate capture that are operative in such systems. Numerous references in the literature indicate that the removal of particulate matter from gas streams by filtration occurs due to a combination of inertial impaction, interception, and diffusion.[3-7] Additional factors such as gravitational, electrostatic, and thermal forces, when present, can also exert their influence on particulate collection efficiency. For purposes of this discussion we will consider the latter forces to be nonoperative in the HEAF system and furthermore, even if present, their contribution to overall collection efficiency is usually insignificant compared to impaction and interception. Therefore, this evaluation will be performed based on the assumption that inertial impaction, interception, and diffusion are the only forces contributing to particulate capture in the HEAF system. The combined target (fiber) collection efficiency will be determined for various particle sizes using individual contributions due to each of the three mechanisms under consideration. The overall fractional efficiency curve of the HEAF fiber mat will be derived using the expression of Bradie and Dickson.[8]

As stated above, particulate collection mechanisms considered in this investigation were inertial impaction, interception, and diffusion. Inertial impaction occurs as a consequence of the relative velocity between the particle and the fluid as the fluid streamlines separate to pass an obstacle in the flow field (a fiber, or a previously deposited particle). Interception or streamline contact with a surface in the flow occurs as a consequence of finite particle size, and diffusion of particles to surfaces of obstacles is a result of Brownian motion. A more detailed discussion of these mechanisms can be found elsewhere.[3-6]

Assumptions underlying particulate capture by these mechanisms are as follows:

1. Collecting obstacles situated in the flow are sufficiently far apart so that the fluid flow in the vicinity of a single obstacle can be represented by the flow near an isolated obstacle; i.e., flow interference effects from adjacent obstacles are neglected.

2. The particles approaching a surface do not interact with or distort the flow to produce additional hydrodynamic lift or drag.

3. The particles always adhere on contact; i.e., bounce, surface migration, and reentrainment are neglected.

The first assumption is required to define the fluid flow field approaching the object. While it is a reasonable assumption for certain very open fibrous filter geometries, in all cases of interest in operating filters, deposits of large numbers of adjacent particles present on the substrate may completely dominate the flow field. However, First and Hinds[7] report that based on their experiments with HEAF mats there is only a very minor influence of fiber interference on filtration efficiency. The second and third assumptions are relatively reliable even in the absence of experimental evidence with this system. Since emissions from asphalt saturators consist of sticky asphalt particulates, it would seem safe to assume that they adhere on contact with the fibers.

The inertial impaction parameter ψ can be expressed as

$$\psi = \frac{C \cdot \rho \cdot V_o D_p^2}{18\mu \cdot D_b \cdot 10^4} \tag{1}$$

where C = empirical correction factor for resistance of gas to movement of small particles

= 1,

ρ = particle density in g/cc (equivalent to asphalt particles)

= 1 g/cc using a sp. gr. of 1.0,

V_o = velocity of particle

= velocity of gas,

D_p = particle size in microns = 0.1, 0.2, 0.3 . . . 1.6,

μ = viscosity of gas in poises = 1.8×10^{-4} poises (for air), and

D_b = diameter of strand in microns = 4 µm. (Manufacturer reported a range of 3.683 to 4.19 µm.)

The inertial parameters were calculated for different particle sizes as a function of velocity and the efficiency of impaction was obtained from Ref. 5 using the experimental curve of η_I versus $\sqrt{\psi}$. These values are shown in Table C-1. The interception efficiency is:[5]

Table C-1. IMPACTION EFFICIENCY AS A FUNCTION OF PARTICLE SIZE AND PARTICLE VELOCITY[a]

D_p (μm)	ψ_1	ψ_2	ψ_3	$\sqrt{\psi_1}$	$\sqrt{\psi_2}$	$\sqrt{\psi_3}$	η_{I_1}	η_{I_2}	η_{I_3}
0.1	0.0157	0.0588	0.0667	0.13	0.24	0.26	0	0	0
0.2	0.0628	0.2352	0.2668	0.25	0.48	0.52	0	0.07	0.09
0.3	0.1413	0.5292	0.6003	0.38	0.73	0.77	0.02	0.22	0.25
0.4	0.2512	0.9408	1.0672	0.50	0.97	1.03	0.08	0.45	0.51
0.5	0.3925	1.47	1.6675	0.63	1.21	1.29	0.17	0.62	0.68
0.6	0.5652	2.1168	2.4012	0.75	1.45	1.55	0.27	0.75	0.80
0.7	0.7693	2.8812	3.2683	0.88	1.70	1.81	0.37	0.86	0.90
0.8	1.0048	3.7632	4.2688	1.0	1.94	2.07	0.50	0.95	0.97
1.0	1.57	-	-	1.25	-	-	0.65	-	-
1.2	2.2608	-	-	1.50	-	-	0.78	-	-
1.4	3.0772	-	-	1.75	-	-	0.88	-	-
1.6	4.0192	-	-	2.0	-	-	0.95	-	-

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[a] Subscripts 1, 2, and 3 refer to velocities of 203 cm/sec, 762 cm/sec, and 864 cm/sec, respectively. The first value is reported to be a typical face velocity of PEDCo Environmental Systems in its report to the EPA (EPA Report No. EPA-650/2-74-101 (October 1974)). The second and third values are face velocities reported by the HEAF manufacturer, who claims that they guarantee device performance only in the range of face velocities provided by these values.

$$\eta_C = 1 + R - \frac{1}{(1 + R)} \qquad (2)$$

where $R = \dfrac{\text{diameter of particle}}{\text{diameter of intercepting body (i.e., strand} = 4\ \mu\text{m)}}$.

These efficiencies were calculated for different particle sizes and are shown in Table C-2.

The diffusional efficiencies, η_D, for different particle sizes were derived from equations in Ref. 5, which relate diffusional efficiency with Peclet Number, Reynolds Number, and Schmidt Number. These values were at least two orders of magnitude smaller than η_I and η_C. Hence they were assumed negligible.

The combined target efficiency has been expressed by Strauss[5] as:

$$\eta_{IC} = 1 - (1 - \eta_I)(1 - \eta_C) \qquad (3)$$

where η_I = efficiency due to impaction, and

η_C = efficiency of interception.

Using the individual efficiencies shown in Tables C-1 and C-2, η_{IC} has been calculated for different particle sizes and velocities. These values are shown in Table C-3. Then, using the expression of Bradie and Dickson,[8] which was developed for a mesh separator, the efficiency can be expressed as shown in Eq. (4). It has been assumed that this equation is also applicable to the HEAF system.

$$E = 1 - \exp(- \frac{2}{3} \pi a \ell \eta_{IC}) \qquad (4)$$

Equation (4) uses the combined target efficiency η_{IC} instead of the collection efficiency due to any one mechanism alone. In Eq. (4)

a = specific area of pad; surface area of fibers per unit volume of pad ($1.34 \times 10^2 cm^2/cm^2$), and

ℓ = length of pad in the direction of flow (0.63 cm).

Table C-2. EFFICIENCY OF INTERCEPTION AS A FUNCTION OF PARTICLE SIZE

D_p (µm)	η_c
0.1	0.0494
0.2	0.0976
0.3	0.1448
0.4	0.1909
0.5	0.2361
0.6	0.2804
0.7	0.3239
0.8	0.3667
1.0	0.450
1.2	0.5308
1.4	0.6093
1.6	0.6857

Table C-3. COMBINED TARGET EFFICIENCY AS A FUNCTION OF PARTICLE SIZE AND PARTICLE VELOCITY[a/]

Dp (μm)	η_c	η_{I_1}	η_{I_2}	η_{I_3}	η_{IC_1}	η_{IC_2}	η_{IC_3}
0.1	0.0494	0	0	0	0.0494	0.0494	0.0494
0.2	0.0976	0	0.07	0.09	0.0976	0.1608	0.1788
0.3	0.1448	0.02	0.22	0.25	0.1619	0.3329	0.3586
0.4	0.1909	0.08	0.45	0.51	0.2556	0.5550	0.6035
0.5	0.2361	0.17	0.62	0.68	0.3659	0.7097	0.7556
0.6	0.2804	0.27	0.75	0.80	0.4747	0.8201	0.8561
0.7	0.3239	0.37	0.86	0.90	0.5741	0.9053	0.9324
0.8	0.3667	0.50	0.95	0.97	0.6834	0.9683	0.9810
1.0	0.450	0.65	-	-	0.8075	-	-
1.2	0.5308	0.78	-	-	0.8968	-	-
1.4	0.6093	0.88	-	-	0.9531	-	-
1.6	0.6857	0.95	-	-	0.9843	-	-

[a/] Subscripts 1, 2, and 3 refer to velocities of 203, 762, and 864 cm/sec, respectively.

The specific area of pad has been computed using a pad density of 31.78 kg/m^3, a glass density of 2,400 kg/m^3, and a fiber size of 4 μm. These values were obtained from the manufacturer. Also the length of pad was reported to be 0.63 cm in the compressed state.

Using Eq. (4) the efficiency of the system was found to be 99.98% for a 0.1 μm particle at a velocity of 203 cm/sec. Therefore, from basic theory, it appears as though the device has a very high collection efficiency even for submicron particulates. The efficiency of the device from field tests is discussed next.

Based on Field Tests

The performance of high energy air filters has been determined by field tests on systems controlling asphalt saturators. Table C-4 shows the results of emission tests conducted by the Los Angeles County Air Pollution Control District (LAAPCD) on four separate asphalt saturators and related equipment.[9] The results are based upon stack sampling and analytical procedures described in detail in the LAAPCD source testing manual.[10] The particulate sampling train used by LAAPCD utilized wet impingement followed by filtration.

Emission tests results shown in Table C-4 indicate total particulate collection efficiencies of 88 to 94%.[9] It is also reported[9] that visible air contaminants were emitted from three of the four filtration systems. The opacities, ranging from 5 to 15% white, showed the adverse effect of condensing organic vapor caused by high effluent temperatures. It is further reported that effluent temperatures should not exceed 54°C to assure compliance with opacity statutes in the LAAPCD area.

Another study reports average particulate collection efficiencies for a HEAF unit ranging from 71 to 87% by weight[11] (see Table C-5). The uncontrolled and controlled samples were not measured simultaneously in this study. Also, sampling of uncontrolled and controlled particulates was done using different sampling trains. For sampling particulates in uncontrolled streams the filter followed the impingers and for controlled streams the filter preceded the impingers.

Even though field tests suggest maximum efficiencies of only 87 to 94% for particulates, it is believed that the unit can achieve higher efficiencies if the inlet gases to the HEAF unit are sufficiently cooled to condense more of the vapors. Until such field tests are made, it will not be possible to determine the unit's highest potential for particulate capture.

Table C-4. ASPHALT SATURATOR EMISSION TESTS[9/]

	Test No.			
	1	2	3	4
Flow rate, Nm^3/min	391	317	1,200	844
Effluent temperature, °C to atmosphere	48	63	68	56
Average filter pressure drop (cm H_2O)	75.9	64.8	69.1	65.0
Usable filter width, cm	53	53	95.3	105.4
Opacity, %	0	5-10	10-15	5-10
Inlet loading, g/Nm^3, dry gas	1.23	0.602	0.863	0.897
Outlet loading, g/Nm^3, dry gas	0.129	0.0494	0.0208	0.0188
Allowable loading, Rule 52, g/Nm^3, dry gas	0.163	0.185	0.129	0.140
Total inlet, particulates, kg/hr	27.4	11.2	14.1	12.0
Total outlet particulates, kg/hr	3.3	0.91	1.0	0.73
Total particulates, overall collection efficiency	88	92	93	94
Total outlet organics, kg/hr as carbon	3.9	1.1	2.3	0.2
Gaseous organics, kg/hr	-	0.3	2.0	-
Asphalt product manufacturer	Shingles	Felt	Shingles	Felt
Saturant temperature, °C	215-220	213	232-243	243

Table C-5. PARTICULATE EMISSION DATA FOR ASPHALT SATURATOR CONTROLLED WITH HEAF[11]

Felt		Process rates (metric ton/hr)		Vent gas[b]			Uncontrolled particulate				Controlled particulate			
									kg/metric ton				kg/metric ton	
Weight[a] (kg)	Moist. (%)	Felt	Product[e]	Flow[c] (Nm^3/min)	Temp. (°C)	Moist. (%)	g/dNm^3[d]	kg/hr	Felt	Product[e]	g/dNm^3[d]	kg/hr	Felt	Product[e]
25.0	3.2	5.22	14.5	850	74	1.5	0.64	31	5.9	2.1	0.156	8.1	1.5	0.56
							0.73	37	7.1	2.6	0.183	9.7	1.9	0.67
							0.32	16	3.1	1.1	0.153	7.0	1.3	0.48
12.3	3.5	1.6	4.0	950	58	1.1	0.53	30	18.8	7.5	0.048	2.4	1.5	0.60
							0.27	16	10.0	4.0	0.037	1.9	1.2	0.48
							0.11	7	4.4	1.8	0.050	2.5	1.6	0.63

---

[a] Kilograms per 44.6 m^2 of felt.

[b] At inlet to control device.

[c] Normal cubic meters per minute corrected to 20°C and 760 mm Hg, dry basis.

[d] Grams per normal cubic meters (dry).

[e] Product is the saturated felt. Saturant used is approximately 1.6 times felt weight.

ECONOMICS

Control system costs are generally estimated on the basis of the exhaust volumes handled. In the roofing industry, exhaust volumes from asphalt saturators can be affected by the type and efficiency of the hooding arrangement, the type of saturation employed (spray-dip, dip, spray), the asphalt characteristics, line width, line speed, felt weight, and moisture content of felt. At present there are no available data to quantify these effects on exhaust volumes. Therefore, costs are indicated for typical exhaust volumes.

Reference 11 reports the installation, operating, and maintenance costs for a HEAF unit operating 6,000 hr/year at 850 actual cubic meters per minute. These are shown in Table C-6. Also included is the cost estimated for 567 Nm^3/min, using information provided by the manufacturer. One roofing plant which has two roofing lines and two HEAF units provided detailed cost data for the HEAF systems. These are shown in Table C-7.

The costs shown in Table C-6, as estimated by MRI, do include the cost involved in cooling the inlet gases to the HEAF unit. Most of the plants do not generally cool the inlet gases to the HEAF. Cooling will condense some of the vapors and increase grain loading. This will favorably affect collection efficiency but may also necessitate more frequent mat replacement.

Table C-6. ECONOMICS OF HEAF SYSTEM FOR CONTROLLING ASPHALT EMISSIONS

	Saturator		Blowing
	Ref. 11 (850 actual m^3/min)	Estimated by MRI (567 Nm^3/min, 5,480 hr/year)	Estimated by MRI (567 Nm^3/min, 2,080 hr/year)
Installed cost ($)	234,000[a]	100,000[c]	100,000[c]
Operating cost ($/year)	22,000	14,000[d,g]	11,700[f,g]
Maintenance cost ($/year)	7,000	5,000[h]	9,000[h]
Depreciation, interest and taxes ($/year)	16,000[b]	15,700[e]	15,700[e]
Total annualized cost ($/year)	45,000	34,700	36,400

---

a/ Cost appears to be very high according to manufacturer and roofing plant personnel (see Table C-7).

b/ Based on 15-year depreciation period.

c/ Unit cost is $64,000 with additional cost of $10,000 for precooling system. Installation cost estimated to be 35% of unit costs. These estimates are based on information from the manufacturer.

d/ Operating cost based on 134 kw for providing 66 cm ΔP and power cost of $0.016/kw-hr (≈ $12,000/year). Operating cost also includes manufacturers estimated mat usage at $0.35/hr (≈ $2,000/year).

e/ Fifteen year depreciation, 9% interest and taxes.

f/ Operating cost based on 134 kw for providing 66 cm ΔP and power cost of $0.016/kw-hr (≈ $4,400/year). Operating cost also includes mat usage which, because of grain loading approximately 10 times higher than in saturator emissions, was assumed to be $3.50/hr per footnote d/ (≈ $7,300).

g/ Not including any additional operating labor costs.

h/ General maintenance (parts and labor) was estimated to be $7.06/$Nm^3$/min based on information from the manufacturer and from plant personnel (≈ $4,000/year). Additional maintenance labor of $1,000/year for mat replacement on saturator was estimated from data supplied by plant personnel. (Additional maintenance labor of $5,000/year for mat replacement on blower unit was estimated from the above, reflecting more frequent replacement due to higher grain loading.)

Table C-7. ECONOMICS OF HEAF SYSTEMS AT ONE ROOFING PLANT[a]

	Unit No. 1	Unit No. 2
Design capacity	1,330 Nm^3/min	850 Nm^3/min
Installed cost	$88,152	$66,826
Annual operating cost (power)	$34,000[b]	$23,000[c]
Annual maintenance	$1,200	$1,500
Annual depreciation[d]	$5,900	$4,500
Annual mat cost[e]	$756	$504
Total annualized cost	$41,856[f]	$29,504[f]

---

a/ Data was obtained during plant survey trip of the facility in November 1974.

b/ Unit No. 1 is equipped with a 220 kw blower and a 22 kw booster fan; operates 8,700 hr/year.

c/ Unit No. 2 is equipped with a 150 kw blower and a 15 kw booster fan; operates 8,700 hr/year.

d/ Based on 15 year depreciation period.

e/ Total mat cost was reported as $1260. Individual costs were estimated using the same proportion of capacities (i.e., ~ 3:2).

f/ Does not include interest on investment.

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APPENDIX D

THEORETICAL ANALYSIS OF THE APPLICABILITY OF VENTURI SCRUBBERS FOR CONTROL OF ASPHALT SATURATOR EMISSIONS

Venturi scrubbers have been used in a variety of applications for many years. Their application to control of particulate emissions from asphalt saturators and air blowing has possibilities, but none have been applied to these sources. Therefore, a theoretical analysis of venturi scrubbers was carried out in an attempt to assess the applicability of venturi scrubbers to control emissions for an asphalt saturator.

In spite of the vast experience gained, there does not exist a reliable design equation for venturi scrubbers. However, Calvert et al.[1/] have developed an equation for predicting particle penetration based upon an analysis of particle and droplet motion in a venturi throat. The following assumptions are involved in use of this equation:*

1. Particles move with the gas at all times and are collected only by liquid drops.

2. Average liquid drop diameter is given by the emperical correlation of Nukiyama and Tanasawa (1938).

$$D_d = \frac{50}{U_G} + 91.8\left(\frac{Q_L}{Q_G}\right)^{1.5} \qquad (1)$$

applicable for $U_G < 7{,}500$ cm/sec.

3. The acceleration of liquid drops may be calculated using the approximation

$$C_D \simeq \frac{55}{Re} \qquad (2)$$

4. The collection of particles by single drops is due to inertial impaction only. Therefore, collection is a function of Stokes number, K_p

$$K_p = \frac{U_r \; \rho_p \; C \; D_p^2}{9 \; \mu_G \; D_d} \qquad (3)$$

---

* See attached table of nomenclature.

5. There is a uniform concentration of particles in any plane perpendicular to the direction of gas flow.

6. Liquid is not atomized and distributed over the cross section until the relative velocity between the liquid and gas is:

$$U_r = fU_G \tag{4}$$

atomization

Here, f is an unknown factor.

Taking into account the continuous change in relative velocity, U_r as the droplets accelerate from the point of their atomization to the gas velocity yielded the following equation:

$$P_t = \exp \left[\frac{2}{55} \frac{Q_L\ U_G\ \rho_L\ D_d}{Q_G\ \mu_G}\ F\ (Kp_t,\ f) \right] \tag{5}$$

Where $F(Kp_t, f)$ is a complicated function of Stokes number and factor f which for Kp_t in the range of 2 to 8 can be approximated by:

$$F(K_{pt},\ f) = -0.156\ K_{pt}\ f^2 \tag{6}$$

Calvert (see Ref. 1, page 5-122, Eqs. 5.3.6-10) developed an equation to estimate the pressure drop in a venturi by assuming that all energy spent in the venturi is used to accelerate the liquid droplets to the throat velocity of the gas.

$$\Delta p = 1.03 \times 10^{-3}\ U_G^2\ \frac{Q_L}{Q_G} \tag{7}$$

By substituting Eq. (6) in Eq. (5) and using Eq. (3), we get:

$$P_t = \exp \left[- \frac{2 \times 10^{-8}}{55}\ \frac{Q_L\ U_G\ \rho_L\ D_d}{Q_G\ \mu_G}\ (0.156)\ \frac{c\ \rho_p\ D_p^2 U_G}{9\ \mu_G\ D_d}\ f^2 \right] \tag{8}$$

From Eqs. (7) and (8) we get:

$$P_t = \exp\left[-6.1 \times 10^{-9} \frac{\rho_L\ C\rho_p\ D_p^2}{\mu_G^2} \Delta p\ f^2\right] \qquad (9)$$

For air/water system at 20°C, and 1 atm,

liquid density, $\rho_L \simeq 1$ gm/cc

particle density, $\rho_p = 1$ gm/cc (assumed).

Cunningham slip correction factor, $C = 1 + 0.162/D_p$

$\mu_G = 183 \times 10^{-6}$ poise

$f = 0.25$

Using the above, Eq. (9) becomes:

$$P_t = \exp\left[-1.138 \times 10^{-2}\ (1 + \frac{0.162}{D_p})\ D_p^2\ \Delta p\right] \qquad (10)$$

Equation (10) shows that the penetration of the particles through the scrubber (P_t = 1 - efficiency) is dependent only on the pressure drop in the venturi and the particle size. The absence of liquid drop size in Eq. (10) indicates that it is a relatively unimportant parameter. Since the penetration is proportional to $\exp(-D_p^2)$, it is primarily a function of particle size.

Pressure Drop Calculations

R. W. Gerstle[2] of PEDCo-Environmental, Inc., has reported particle size distribution of uncontrolled saturator exhaust. The data were obtained using a Brinks impactor. The data taken off their graph are tabulated in Table D-1.

In the literature, the density of asphalt particles is given as approximately equal to one.[3] Therefore, particle diameter listed in Table D-1 is equal to aerodynamic particle diameter. The overall penetration, $\bar{P}_t$ for a control device can be calculated from Eq. (12).

$$\bar{P}_t = \int_0^\infty P_t(D_p)\ f\ (D_p)\ dD_p \qquad (12)$$

Table D-1. TABULATION OF PARTICLE SIZE DISTRIBUTION DATA FOR ASPHALT SATURATOR EMISSIONS

	D_p	D_{pi}	x[a]	Cum % w ≤	ΔM_i	$\frac{\Delta M_i}{\Delta \log D_p}$
	0.22			0	0	
	0.28	0.25	1.172×10^{-3}	1	1	9.55
	0.3	0.29	1.492×10^{-3}	4	3	100.12
	0.31	0.305	1.621×10^{-3}	10	6	421.34
	0.36	0.335	1.895×10^{-3}	20	10	153.99
	0.41	0.385	2.397×10^{-3}	30	10	177.05
	0.52	0.465	3.318×10^{-3}	40	10	96.88
	0.77	0.645	5.924×10^{-3}	50	10	58.66
	1.50	1.135	1.675×10^{-2}	60	10	34.58
	4.0	2.75	9.113×10^{-2}	70	10	23.48
Extrapolation ↓	10.0	7	5.705×10^{-1}	90	20	50.26
	20.0	15	2.588	100	10	33.22

---

[a] The factor x in the table comes from equation (10) and is defined as

$$x = 1.138 \times 10^{-2} \left(1 + \frac{0.162}{D_p}\right) D_p^2 \qquad (11)$$

Equation (12) for tabulated data (Table D-1) can be written as:

$$\overline{P}_t = \sum_i P_t(D_{pi})\,\Delta M_i \qquad (13)$$

Using Eq. (10) and tabulated values of ΔM_i, the penetration as a function of size, and the overall penetration, is obtained. The overall collection efficiency for different values of Δp are given in Table D-2. The U_G at Δp of 1,000 cm H_2O and Q_L/Q_G of 0.001 is 31,158 cm/sec. At this velocity the K_{pt} calculated from Eq. (3) is 43.3. This shows that the Δp's obtained in these calculations are probably too low, by a factor of 2, due to large values of $F(K_{pt}, f)$ predicted by Eq. (6).

Discussion

The pressure drops needed for the control of asphalt saturator emissions with particle size distribution as listed in Table D-1 are very high. There are many reasons why we obtained this high estimate of pressure drops. Principal reasons are:

1. As can be seen in Table D-1, the median size of asphalt particles is 0.77 μm, which is a fine aerosol.

2. The theory developed by Calvert[1/] considers only the collection by inertial mechanisms. For small particles (< 1 μm) collection by inertia is small compared to collection by diffusion or electrostatic attraction. Also, at very high throat velocities (in the present case the velocities reached are sonic velocities) turbulent agglomeration and subsequent inertial collection can take place.

3. The equations developed for calculating liquid droplet diameter (Eq. (1)) and the equation to calculate the drag (Eq. (2)) are not valid at high throat velocities estimated in this calculation.

Considering the above points, it is possible that the theoretical analysis used herein may not be entirely valid. However, the results do confirm the expectation that a very high pressure drop venturi scrubber would be required for efficient removal of the small particle size emissions from asphalt saturators. In fact, the pressure drops required are much higher than that of even the highest pressure drop venturies (~ 254 cm H_2O) and the associated power requirements would be exhorbitant. This may partially explain those statements of opinion by others that scrubbers are not a viable control method for this source.

Table D-2. OVERALL EFFICIENCY OF REMOVAL FOR ASPHALT SATURATOR PARTICULATE VERSUS PRESSURE DROP

ΔP (cm H_2O)	Overall efficiency (%)
50	52.5
100	60.7
500	86.0
1,000	95.0
1,500	98.0
1,875	99.0

NOMENCLATURE (APPENDIX D)

C = Cunningham slip correction factor

C_D = Coefficient of drag

D_d = Liquid droplet diameter (μm)

D_p = Particle diameter (μm)

F = Function of K_p and f

f = Nonuniformity and unknown factor in the atomization and subsequent acceleration of liquid drops

0.1 to 0.3 for hydrophobic drops
0.5 for hydrophelic drops

K_p = Stokes number

K_{pt} = Stokes number calculated at throat gas velocity

P_t = Penetration (1 - efficiency)

$\overline{P}_t$ = Overall penetration

Δp = Pressure drop in (cm H_2O)

Q_G = Volume flow rate of gas (m^3/sec)

Q_L = Volume flow rate of liquid (m^3/sec)

R_e = Liquid droplet Reynolds number

V_G = Gas velocity at the throat (cm/sec)

U_r = Relative velocity of particles with respect to droplets (cm/sec)

ρ_p = Particle density (gm/cc)

ρ_L = Liquid density (gm/cc)

μ_G = Gas viscosity (poise)

REFERENCES FOR APPENDIX D

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APPENDIX E

EVALUATION OF ELECTROSTATIC PRECIPITATORS FOR CONTROLLING EMISSIONS FROM ASPHALT SATURATORS/BLOWERS

INTRODUCTION

Electrostatic precipitators (ESP) utilize the forces acting on an electrically charged particle in an electric field to remove the particles from a gas stream. These forces move the particles to the wall where they can be collected. In the collection of dry particles, a layer of dust builds up on the wall and is periodically removed by various methods. In some instances, the wall is wetted by a film of liquid (e.g., water) that continuously runs off, thereby removing the particles. This type of installation requires further processing steps to remove the particulate from the liquid before the liquid is discharged to the environment or recycled for further use.

The fundamental advantage of ESP units over many other particulate control devices is their relatively low energy consumption. In ESP units, the separation forces are applied directly to the particles instead of to the entire gas stream, as in most mechanical separation methods. High collection efficiency, low resistance to gas flow, the ability to treat large gas quantities at high temperatures, and the ability to cope successfully with corrosive atmospheres account for the wide acceptance and diverse applications of the electrostatic precipitation process.

THEORY OF ESP OPERATION

Electrostatic precipitators are conventionally classified as single or two stage units.[1/] In a single stage unit, the particle charging and collecting sections coincide as shown schematically in Figure E1-A. In a two stage unit, shown schematically in Figure E1-B, the charging and collecting sections are separate. ESP units can be further classified according to their geometry, the two most common classifications being flat plate and cylindrical plate configurations. Regardless of classification, the collection efficiency for design purposes is described by the Deutsch equation (Eq. (6.22) of Ref. 1) as:

$$\eta = 1 - e^{-(Aw/v)} \qquad (1)$$

where η = collection efficiency
w = particle migration velocity (m/sec)
A = collecting area of precipitator (m^2)
V = gas volumetric flow rate through the precipitator (m^3/sec)

This relation shows that the collection efficiency of a particular device increases with:

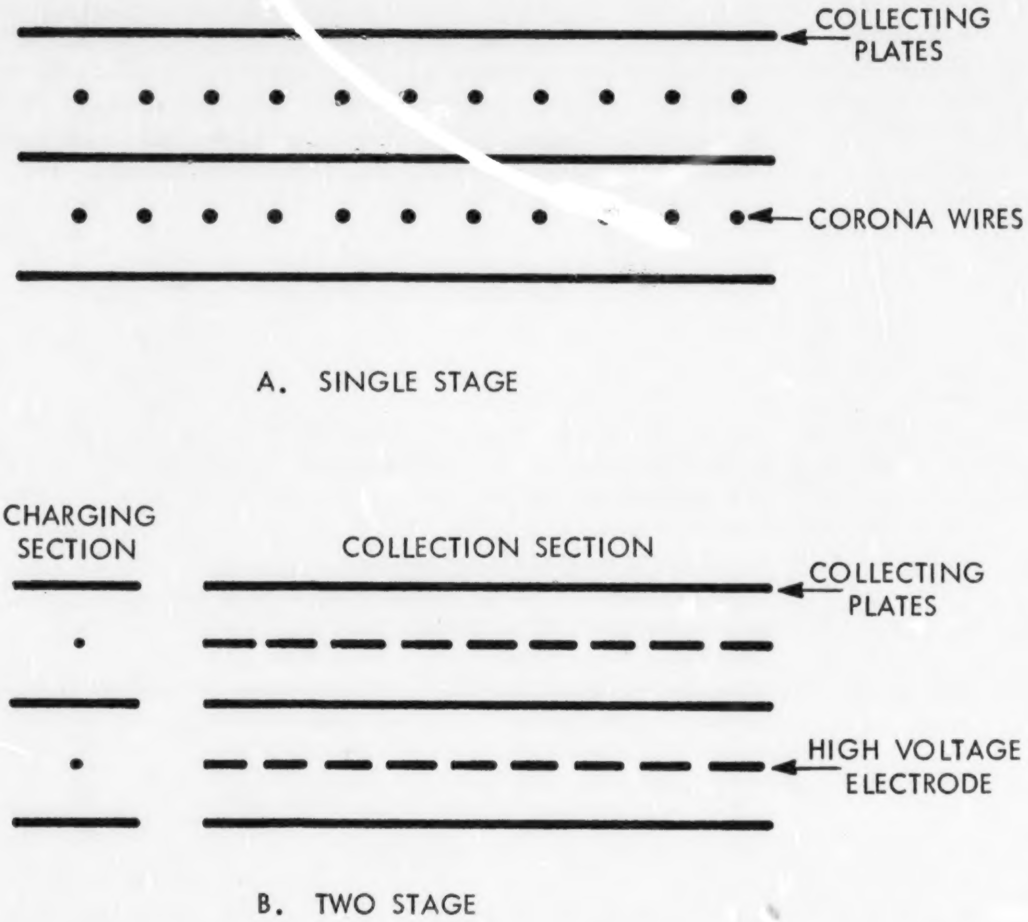
COLLECTING PLATES
CORONA WIRES
A. SINGLE STAGE
CHARGING SECTION
COLLECTION SECTION
COLLECTING PLATES
HIGH VOLTAGE ELECTRODE
B. TWO STAGE

Figure E-1. General Classification of Electrostatic Precipitators

- * increasing specific collection surface (A/V)
- * increasing place collection area (A)
- * decreasing gas volumetric flow rate (V)
- * increasing particle migration velocity (w)

The effect of particle size on collection efficiency is incorporated in the particle migration velocity. In designing and sizing a unit for a specific application, the particle migration velocity is determined experimentally through measurements of collection efficiency and the specific collection surface. When estimated in this fashion, the migration velocity reflects a number of effects that are not easily modeled in an analytical theory (e.g., particle reentrainment effects, nonuniform electric fields, particle shape effects, etc.). To gain insight into the primary factors governing the migration velocity, theoretical analysis has been employed and shows that migration velocity is given by (Eq. (6.3), Ref. 1): (see note)

$$w = \frac{q\ E_p \times 10^7}{6\pi\ \mu a}\left(1 + A_1 \frac{\lambda}{a}\right) \tag{2}$$

where w = migration velocity (cm/sec)
q = charge on the particle (coulombs)
E_p = collection section field strength (volts/cm)
μ = gas viscosity (poise)
a = particle radius (cm)
A_1 = Cunningham correction constant
= 0.86 for air at normal temperature and pressure
λ = molecular mean free path (cm)

One notes from the above equation that the migration velocity increases with:

- * increasing charge on the particle (q)
- * increasing collection section electric field (E_p)
- * decreasing gas viscosity (μ)

Equation (2), taken by itself, indicates that the migration velocity increases with decreasing particle size. However, the charge acquired by a particle in the charging section of ESP units depends on the particle size. Therefore, a brief discussion of particle charging is in order.

Note: Equations taken from Ref. 1 have been converted from esu units to more practical electrical units.

As pointed out in Ref. 1, particles may be charged in numerous ways by taking advantage of the varied electric activity associated with many physical and chemical phenomena. Theory and long experience have shown that the unipolar high-voltage corona discharge is by far the best and most universally applicable means for achieving very high particle charges for gas cleaning purposes. Two distinct particle charging mechanisms are active in the corona field of a precipitator, the most important of which is charging by ion attachment in the electric field. This is a process that is generally designated as field or impact charging. A secondary charging process occurs due to the phenomenon of ion diffusion. In practice, the field charging process predominates for particles larger than about 0.5 µm diameter, the diffusion process for particles smaller than about 0.2 µm, while both are important for particles in the intermediate range of 0.2 to 0.5 µm. Theoretical relations for the rate of charging by these two mechanisms have been developed (e.g., Eq. (5.27) for diffusion charging and Eqs. (5.15) and (5.17) for field charging, Ref. 1). One of the most important differences between the two mechanisms is that the charge increases continuously with time of exposure in diffusion charging but reaches a constant value relatively quickly for field charging. This apparent advantage of diffusion charging cannot be realized in practice, however, because of the large exposure time required. To illustrate this point, calculations were made for a 0.1 µm diameter particle, assuming an ion density of 5×10^8 ions/cm^3, a gas temperature of 60°C, a dielectric constant of 2 (typical for oil), and a charging field strength of 10^4 v/cm. The results of these calculations are presented in Table E-1. One notes that the field charging mechanism increases the charge rapidly at small values of time but the charge reaches a constant value after 0.1 sec. The diffusion charging mechanism, however, increases the charge continuously, eventually surpassing the field charge (at ~ 0.1 sec). However, the full potential of diffusion charging (e.g., 4.68 times the field charge at t = 1,000 sec) cannot be realized in practical applications because of the excessive treatment time required.

In order to simplify the remaining discussion, only the field charging mechanism will be utilized in the remainder of this section. The resulting expressions should be reasonably accurate down to 0.5 µm particles. The theoretical saturation charge acquired by a particle due to field charging is given by (Eq. (5.17), Ref. 1):

$$q = \left(1 + 2\,\frac{k-1}{k+2}\right)\frac{E_o a^2}{9} \times 10^{-11} \qquad (3)$$

where q = saturation charge on a particle (coulombs)
k = dielectric constant of the particle
E_o = charging field strength (volts/cm)

Table E-1. NUMBER OF ELEMENTARY CHARGES ACQUIRED BY A 0.1 μm PARTICLE AS A FUNCTION OF TIME BY DIFFUSION AND FIELD CHARGING

	Number of charges		Ratio of diffusion
Time (sec)	Diffusion charging	Field charging	to field charge
0.001	0.18	0.87	0.21
0.01	1.09	2.17	0.50
0.1	3.03	2.55	1.19
1.0	5.29	2.59	2.04
10.0	7.58	2.60	2.92
100.0	9.88	2.60	3.80
1,000.0	12.18	2.60	4.68

Combining relations (2) and (3) gives:

$$w = 5.89 \times 10^{-7} \left(1 + 2\,\frac{k-1}{k+2}\right)\left(1 + A_1\,\frac{\lambda}{a}\right)\frac{E_o E_p a}{\mu} \qquad (4)$$

When presented in this form, one observes that the migration velocity (assuming field charging) and collection efficiency increase with:

- * increasing particle size (a)
- * increasing charging and collection fields (E_o,E_p)
- * decreasing gas viscosity (μ)

THEORETICAL CALCULATIONS FOR SATURATOR OPERATIONS

The dielectric constant for petroleum oil is approximately two, which, when substituted into relation (4) gives (at normal temperatures and pressures):

$$w = 8.8425 \times 10^{-7} \left(1 + 0.86\,\frac{\lambda}{a}\right)\frac{E_o E_p a}{\mu} \qquad (5)$$

Air, at 60°C, has a viscosity of 2.03×10^{-4} poise and a mean free path of approximately 0.1 μm. Using these values, introducing $a = d/2$, and converting diameter (d) to micrometer units provides:

$$w = 2.178 \times 10^{-7} \left(1 + \frac{0.172}{d}\right) E_o E_p d \qquad (6)$$

This relation is applicable for particles above 0.5 μ diameter. As discussed previously, for smaller particles, diffusion charging becomes important and must be taken into account. A hypothetical example of a modular ESP collection plate configuration is shown in Figure E-2. Assuming a plate voltage of 6,500 v, the plate field is 6,500 v/cm. The collection area of one side of a grounded plate is 0.26 m^2 and the total collection area is 12.9 m^2. Assuming an air flow of 1.83 m/sec, with the inflow area of 50 x 50 = 2,500 cm^2 (= 0.25 m^2), the volumetric flow rate is 27.5 m^3/min. Thus, the specific collection surface is:

$$A/v = \frac{12.9\ m^2}{27.5\ m^3/min} = 0.469\ min/m$$

Assuming a charging section field strength of 10,000 v/cm together with the plate field of 6,500 v/cm, relation (6) becomes:

$$w\ (cm/sec) = 14.81\ (1 + \frac{0.172}{d})d \tag{7}$$

Substituting the specific collection surface and relation (7) into (1) gives:

$$\eta = 1 - e^{-4.12\ (1 + \frac{0.172}{d})d} \tag{8}$$

where d is in units of micrometers

According to Figure E-3 (taken from Figure 4.2, Ref. 2), 50% of the particulate mass from saturator operations is contained in particles less than about 0.8 μm in diameter. Similar particle size data have not yet been found for the emissions from the blowing operation. Using efficiencies calculated with Eq. (8), along with the overall size distribution from Figure E-3, Table E-2 has been prepared. The overall mass collection efficiency is seen to be 94.74% on a single module based on the theoretical calculations. If a second collection unit were to follow the first module, further increases in efficiency would be realized. Such a configuration would be equivalent to doubling the collection plate area (and the specific collection surface) leading to:

$$\eta = 1 - e^{-8.24\ (1 + \frac{0.172}{d})d} \tag{9}$$

The results of calculations with Eq. (9) are shown in Columns 6 and 7 of Table E-2 with a resulting overall efficiency of 99.27% for tandem units.

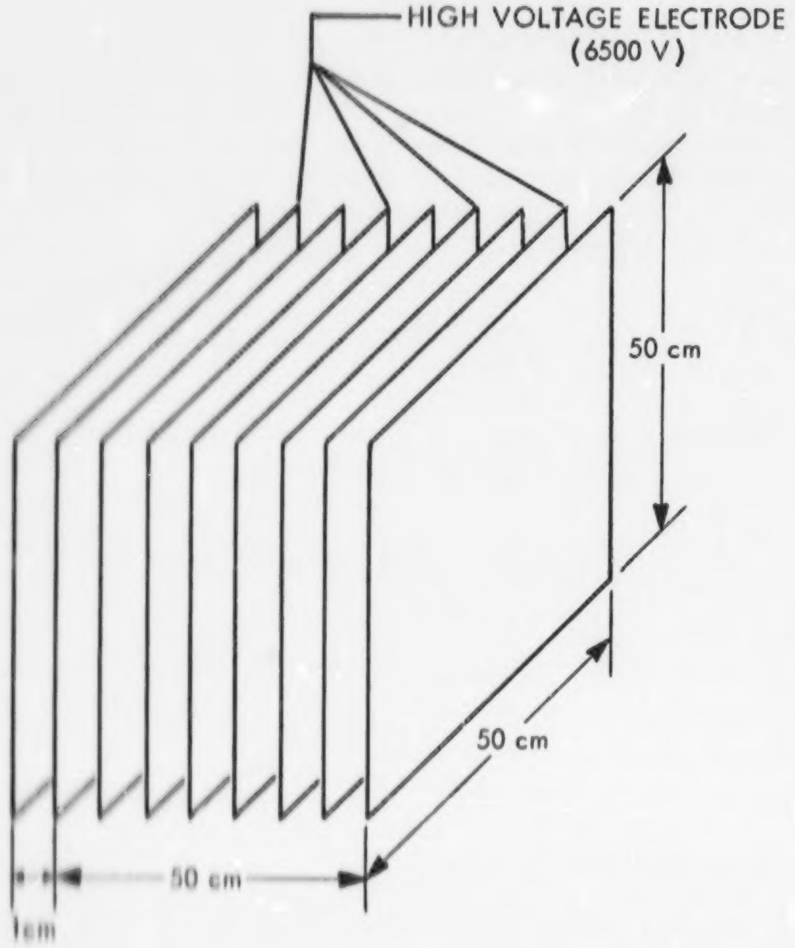
HIGH VOLTAGE ELECTRODE (6500 V)
50 cm
50 cm
50 cm
1cm

Figure E-2. Hypothetical ESP Collection Plate Configuration

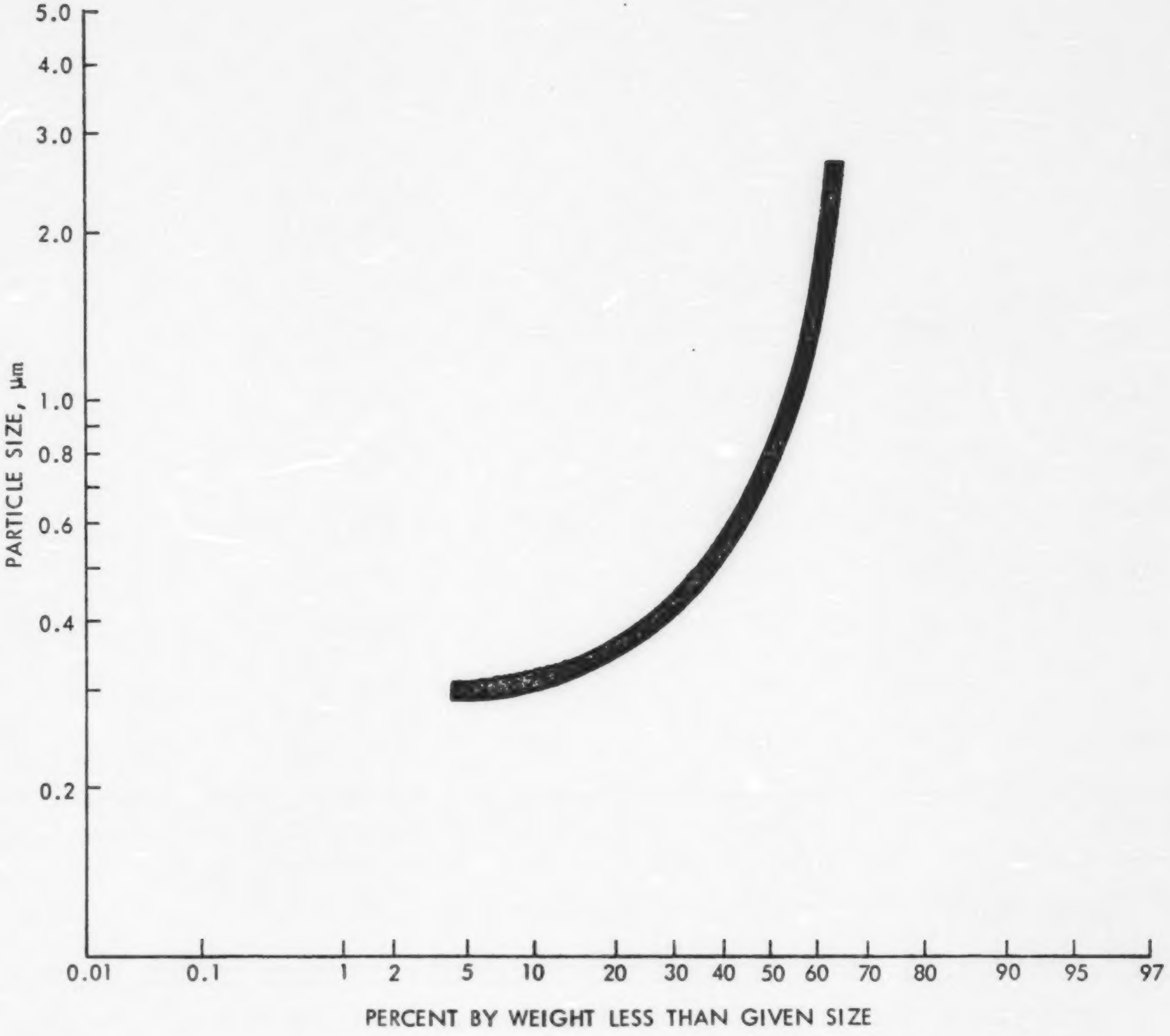

Figure E-3. Particle Size Distribution in Uncontrolled Saturator Exhaust

Table E-2. THEORETICAL OVERALL AND FRACTIONAL EFFICIENCIES FOR SATURATOR OPERATIONS

		Single module			Tandem modules	
(1) Particle size range (μm)	(2) Mean particle size (μm)	(3) Fractional efficiency (Eq. 8)	(4) Mass fraction (Figure E-3)	(5) Mass fraction removed (3) x (4)	(6) Fractional efficiency (Eq. 9)	(7) Mass fraction removed (4) x (6)
0-0.3	0.15	0.7346	0.05	0.0367	0.9296	0.0465
0.3-0.4	0.35	0.8835	0.20	0.1767	0.9864	0.1973
0.4-0.5	0.45	0.9229	0.14	0.1292	0.9941	0.1392
0.5-0.6	0.55	0.9489	0.06	0.0569	0.9974	0.0598
0.06-0.8	0.70	0.9725	0.05	0.0486	0.9992	0.0499
0.8-1.0	0.90	0.9879	0.05	0.0494	0.9999	0.0500
1.0-2.0	1.50	0.9990	0.10	0.0999	1.0	0.10
2.0-∞	-	1.0	0.35	0.35	1.0	0.35
Total	-	-	1.00	0.9474	-	0.9927

Based on theoretical calculations, it appears that modular type ESP units can effectively remove up to 99% of the particulate asphalt emissions from saturator operations. However, it must be noted that this can be achieved only for those pollutants that are in particulate form. As pointed out in this report, uncontrolled emissions from saturators probably contain a significant amount of gaseous hydrocarbons. Under these conditions, any collection device that is ineffective in collecting gaseous components (e.g., ESPs, HEAF) can achieve a maximum total hydrocarbon efficiency only equal to the percentage of particulate hydrocarbons. Thus, preconditioning or cooling of the gas stream is required for these devices to reduce the gaseous hydrocarbon component to an assumed low level in order to achieve 95 to 99% removal of total hydrocarbons. The gaseous component in asphalt blowing operations is believed to be at least as much as that found in saturator operations and, therefore, would also necessitate preconditioning or precooling to maximize condensation of gaseous hydrocarbons.

USE OF ESP UNITS IN THE ASPHALT ROOFING INDUSTRY

According to an MRI survey, 10 of 76 saturator installations control their effluent emissions with ESP units. In an attempt to further define the applicability of ESP units in the asphalt roofing industry, a number of individuals and manufacturers have been contacted. One of our first attempts was to find a more detailed and complete model of ESP operation characteristics than the simplified approach presented in the previous sections of this report. It was found that Southern Research Institute has developed a computerized model for wire-plate precipitator geometries. As of this writing, the final report detailing the development of this model has not been completed for general distribution. Conversations with individuals responsible for the development of the model indicated that it was best suited for evaluating a given proposed configuration with known geometry, voltage-current relationship, particle size distribution, and gas flow rate. As such, this model may prove useful in future design efforts but is not directly useful for the more general investigation being undertaken in the present study.

Four firms engaged in the manufacturing of electrostatic precipitators were contacted in an attempt to obtain field test results for typical operations encountered in the asphalt roofing industry. Only one of these manufactures a unit that has been utilized to any degree in the asphalt roofing industry. The various ESP units manufactured by these companies, together with relevant field test data whenever they existed, are discussed in the following paragraphs.

United Air Specialists, Inc., in Cincinnati, Ohio, manufactures a modular, two stage unit designated the "Smog-Hog"™. A schematic diagram of this unit is shown in Figure E-4. Several of these units are presently installed to control emissions from the saturator process. According to one of United's

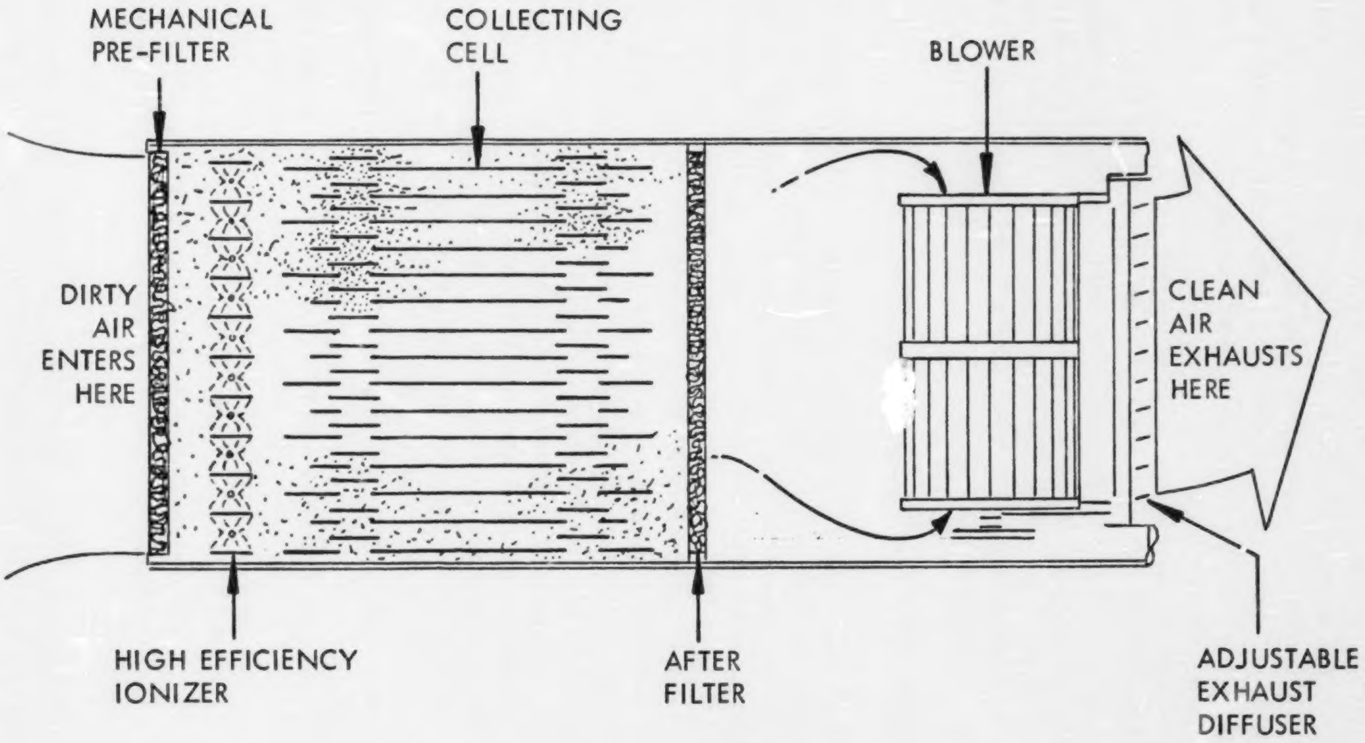
MECHANICAL
PRE-FILTER
COLLECTING
CELL
BLOWER
DIRTY
AIR
ENTERS
HERE
CLEAN
AIR
EXHAUSTS
HERE
HIGH EFFICIENCY
IONIZER
AFTER
FILTER
ADJUSTABLE
EXHAUST
DIFFUSER

Figure E-4. Schematic of "Smog-Hog"™

representatives, they presently have orders for installation of their system in 30 asphalt saturator plants. About half of these were to be installed by the end of July 1975. This representative said that their units would not work well in asphalt blowing operations because of the high grain loading (average of 8.4 g/Nm^3) but that they worked well on saturators (average grain loading of 0.80). He believed that a 2.3 g/Nm^3 loading was about the upper limit for acceptable saturator emission control with their units.

In typical installations, they use tandem units to achieve emission control of particulate hydrocarbons. The units have a 12 KV ionizing section and 6 KV collection plates. For proper operation, inlet air must be at or below 60°C. Depending on plant layout, length and insulation of ducts, precooling is sometimes necessary to achieve this temperature level. A premist or high pressure spray is normally included to reduce maintenance frequency. A typical installation including a plenum chamber, prefilters, and tandem pass units have a capital cost of \$88.25/Nm^3/min. Operation and maintenance costs average \$0.18/hr/100 Nm^3/min capacity. If the loading is especially heavy caused by fast run, low boiling point asphalt, high moisture, etc., then a triple pass "Smog-Hog"™ is necessary. The capital cost of this system would be approximately \$123.55/Nm^3/min. If the temperature exceeds 60 to 66°C at the inlet, then a precooling or condensing device must be utilized. The cost of these units vary, depending on the type of precooler used.

Performance data for two plants are presented in Tables E-3 and E-4. Table E-3 contains data collected at the Celotex Corporation in Lockland, Ohio, on two different occasions. Average filterable particulate efficiency for the two tests is 91.3%. Average total efficiency is 74.3%. The efficiency for condensible matter averages 54.2%.

The units installed in this plant were single-pass "Smog-Hogs"™ which are less efficient than the usual tandem pass units. Also, the inlet and outlet sampling were not performed simultaneously, or a considerable loss in exhaust gas occurred through the unit, as is evidenced by the large differences in inlet and outlet flow rates. Also, the average inlet loading is only 0.066 g/Nm^3, a very low value compared with the previous average of 0.80 g/Nm^3.

Tests conducted on a tandem unit installation at the Celotex Corporation in Fairfield, Alabama, are summarized in Table E-4. The average efficiency for filterable particulates, condensible matter and total emissions is 98.7, 86.4, and 95.4%, respectively. It is interesting to note the higher condensible matter efficiencies in Table E-4 as compared with Table E-3. This is probably due to the lower gas temperatures for the tests in Table E-4 which would lead to a higher percentage of condensation and subsequent capture in the ESP unit. Also, the tests of Table E-3 were performed with simultaneous

Table E-3. TESTS AT CELOTEX CORPORATION, LOCKLAND, OHIO

					Filterable particulate			Condensible matter[c]			Total		
Date 1974	Unit No.	Flow (Nm^3/min)[a]	Temp. (°C)	Sample site	g/Nm^3[b]	kg/hr	Eff. (%)	g/Nm^3	kg/hr	Eff. (%)	g/Nm^3	kg/hr	Eff. (%)
4/9	1	552	61	Inlet	0.043	1.43	-	0.034	1.13	-	0.078	2.56	-
4/9	1	428	49	Outlet	0.0027	0.073	94.9	0.02	0.56	50.6	0.025	0.63	75.3
4/16	1	649	52	Inlet	0.027	1.10	-	0.025	1.02	-	0.053	2.12	-
4/16	1	416	49	Outlet	0.0054	0.14	87.6	0.018	0.43	57.8	0.02	0.57	73.2

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a/ Normal cubic meter per minute, corrected to 20°C, 760 mm Hg--dry basis.
b/ Grams per normal cubic meter
c/ Included particulate condensible down to the 10 to 20°C range.
Note: Tests are for single-pass "Smog-Hog"™ units with a fiber roll prefilter.

Table E-4. TESTS AT CELOTEX CORPORATION, FAIRFIELD, ALABAMA (MARCH 4 AND 5, 1975)

				Filterable particulate			Condensible matter[c]			Total		
Test No.	Flow (Nm^3/min)[a]	Temp. (°C)	Sample site	g/Nm^3[b]	kg/hr	Eff. (%)	g/Nm^3	kg/hr	Eff. (%)	g/Nm^3	kg/hr	Eff. (%)
1	587	30	Inlet	0.117	4.13	-	0.0103	0.36	-	0.128	4.49	-
1	602	29	Outlet	0.00103	0.037	99.1	0.00140	0.050	86.1	0.0025	0.087	98.0
2	567	34	Inlet	0.117	4.00	-	0.071	2.40	-	0.188	6.40	-
2	585	32	Outlet	0.00110	0.039	99.0	0.00906	0.322	86.6	0.0103	0.361	94.4
3	569	34	Inlet	0.011	3.75	-	0.0600	2.04	-	0.169	5.79	-
3	593	33	Outlet	0.00208	0.074	98.0	0.0078	0.277	86.4	0.0098	0.351	93.9

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a/ Normal cubic meters per minute, corrected to 20°C, 760 mm Hg--dry basis.
b/ Grams per normal cubic meter.
c/ Included particulate condensible down to the 10 to 20°C range.
Note: Tests are for tandem "Smog-Hog"™ units with a fiber roll prefilter.

sampling of the inlet and outlet of the control units, providing a higher confidence in the tests results. The average inlet loading is 0.162 g/Nm^3, again considerably below the previous average.

It is interesting to note the percent condensibles at the inlet in Tables E-3 and E-4. Table E-3 indicates an average inlet condition with 46.2% condensibles compared with an average of 26.9% in Table E-4. It is possible that the filter in the sampling train became fully loaded with subsequent penetration of liquid asphalt through the filter that was subsequently captured in the impingers and reported as "condensible." Further studies to establish the percent of gaseous hydrocarbons appears needed.

A representative of the American Air Filter Company was contacted to obtain information relative to their ESP units. They presently manufacture a two stage ESP unit that they call the Environmental Control Unit (ECU) which apparently is similar to the "Smog-Hog"™. The ionizer wires are maintained at 12,400 volts DC and the collection plates are energized to 6,500 volts. The ECUs are equipped with an internal cold water washing system that can also dispense various detergents. These units are intended for the control of visible concentrations of mists and fumes, and the representative believed they would work satisfactorily on asphalt saturator emissions. However, the representative's experience with asphalt blowing operations led him to believe the units would not function effectively in this application because of the fouling and cleaning problems produced by the tar-like buildup on the collection plates, insulators, etc. They have not been able to find a detergent suitable for removing these tar deposits. Equipment capital costs amount to approximately $31.77/Nm^3/min (which seems rather low). Additional costs for ducting is dependent on plant layout, etc., and are quite variable. If additional gas conditioners for precooling are needed, they can run $17.65 to $70.60/Nm^3/min.

A representative of Fluid-Ionic Systems was contacted relative to their "Hydro-Precipitrol"™ ESP units. The units are cylindrical and composed of several concentric wetted wall collection plates and expanded metal ionizing cages, and would be classified as single stage precipitators. Their largest unit, 3.8 m in diameter, can handle up to 2,550 Nm^3/min of effluent gases in some applications. The units operate in a voltage range of 38 to 42,000 volts. Although they do not presently have any of their units installed at asphalt saturator or blowing plants, they do have some test data collected several years ago. The data, summarized in Table E-5, were obtained on a saturator operation with a small, portable "Hydro-Precipitrol"™ unit comprised of two cylindrical collection plates (76.2 and 50.8 cm diameter) and one expanded metal ionizing cage (63.5 cm diameter). The unit had a plate length of 1.5 m. Using these dimensions, it is estimated that the

Table E-5. TEST DATA OBTAINED FOR A SMALL "HYDRO-PRECIPITROL"™ UNIT FOR A SATURATOR APPLICATION

				Filterable particulate			Condensible matter			Total		
Test No.	Flow (Nm^3/min)	Temp. (°C)	Sample site	g/Nm^3	kg/hr	Eff. (%)	g/Nm^3	kg/hr	Eff. (%)	g/Nm^3	kg/hr	Eff. (%)
1	37.1	38	Inlet	0.0460	0.1025	-	0.0032	0.0071	-	0.0492	0.1096	-
1	48.8	26	Outlet	0.0021	0.0060	94.1	0.0009	0.0027	62.4	0.0030	0.0087	92.0
2	53.0	37	Inlet	0.0474	0.1508	-	0.0050	0.0160	-	0.0524	0.1668	-
2	64.2	26	Outlet	0.0032	0.0124	91.8	0	0	100.0	0.0032	0.0124	92.6
3	55.0	33	Inlet	0.0362	0.1194	-	0.0069	0.0227	-	0.0430	0.1421	-
3	68.7	26	Outlet	0.0032	0.0132	88.9	0.0016	0.0066	70.7	0.0048	0.0198	86.0
4	79.8	32	Inlet	0.0339	0.1625	-	0.0183	0.0878	-	0.0522	0.2503	-
4	102.5	26	Outlet	0.0041	0.0254	84.4	0.0007	0.0042	95.2	0.0048	0.0296	88.2

unit had a flow area of 0.25 m^2 and a collection plate area of 6.1 m^2. Referring to Table E-5, one finds that based on the four tests, the average filterable, condensible, and total removal efficiencies are 89.8, 82.1, and 89.7%, respectively. Referring to the flow column indicates that there apparently was considerable secondary air leakage into the unit during the tests. Also, the air temperatures are relatively low, probably due to a preconditioner incorporated into the ESP unit.

On the average, condensible matter amounted to 16.8% of the hydrocarbon at the inlet. Once again, the average inlet loading was low, averaging 0.50 g/Nm^3 for the four tests. The company would not provide any cost data for their unit since each potential application has unique features and operating requirements. They believed a general cost figure would be misleading and not appropriate without specific tests on a process using one of their small, portable units.

A representative of the MikroPul Division at United States Filter Corporation, Summit, New Jersey, was also contacted relative to their "Elektrofil"™ wet electrostatic precipitator. These units are large, the minimum standard size presently manufactured being a 1,416 Nm^3/min. Thus, it does not appear feasible to utilize the "Elektrofil"™ standard units in asphalt roofing industry. However, smaller units could undoubtedly become standard if a sufficient market existed. In fact, the company is presently looking into the possibility of manufacturing modular units. Specially designed smaller units can be obtained, but at an increased cost per cubic feet per minute capacity. The unit operates with a continuous flow of fine liquid droplets into the ionizing section. These droplets become charged and migrate to the collection plates, forming a continuous film of liquid. The company has had no applications in the asphalt roofing industry but has had applications of their units for the treatment of oil and tar emissions.

According to the MikroPul representative, a 1,416 Nm^3/min, three stage unit, constructed with carbon steel, has a capital cost of \$229.45/Nm^3/min. Installation costs typically add 30% to this cost and operating costs are 0.053 to 0.071 kw/Nm^3/min capacity. Water usage amounts to 0.80 to 0.93 liters/Nm^3.

When any particulate collection device (e.g., ESP or HEAF) is used to control the effluent from saturator operations, proper gas preconditioning is very important for assuring maximum condensation of asphalt vapors. The importance of preconditioning was emphasized by the plant superintendent of the Bird and Son facilities in Portland, Oregon, who was contacted to obtain information on the operation of their ESP unit. The saturator emissions from their operation are controlled by a Type B American Air Filter Rotoclone wet centrifugal dust collector and an American Air Filter Type S electrocell ESP unit (this ESP unit is no longer being manufactured). The unit has provided good emission control in this plant but no quantitative data are available. The superintendent believed that the long duct (about 55 m long, 99 cm diameter), containing spray nozzles over its entire length, was very beneficial in achieving good emission control. A similar emission control system in a competitor's plant has not worked effectively and the only major difference is the duct length and associated spray nozzle system.

The use of wet electrostatic precipitators on asphalt air-blowing or saturator operations might present a potential water pollution problem if the hydrocarbon/water emulsion were difficult to "break." It has been assumed in these discussions that the effluent emulsion could be separated probably with the aid of emulsion breakers, so that the water could be recycled to the ESP and the separated asphalt could be returned to the process. However, if the emulsion were very difficult to break, this might present a potential water pollution problem that could detract from, or offset, possible advantages of the wet electrostatic precipitators.

ECONOMICS AND COST ESTIMATES

All of the following cost estimates are based on information supplied by the four manufacturers contacted during the study. Dry precipitator estimates are based on data for the "Smog-Hog"™ and Environmental Control Unit. Wet precipitator estimates are based on the data supplied for the "Elektrofil"™ unit, since no cost data could be obtained for the "Hydro-Precipitrol."™ Saturator costs are based on a gas flow rate of 567 m^3/min and 5,480 hr/year operating time. Estimated efficiencies are based on reported test data. However, these test data are for relatively low inlet concentrations (0.043 to 0.188 g/Nm^3) and extrapolation of these efficiencies to higher loadings may be overly optimistic.

Cost estimates for tandem and triple pass "Smog-Hog"™ units are presented in Table E-6. Based on the available experimental data, it appears that a tandem unit can achieve a 95% efficiency at a total annual cost of $18,800. A triple pass unit should achieve about 99% removal efficiency at an annual cost of $23,700.

A cost estimate for the Environmental Control Unit is presented in Table E-7. The company's representative had no test data for this unit controlling asphalt saturator emissions. However, he believed it would function at about the same efficiency as their older Model S ESP units (no longer manufactured) and quoted an efficiency value of 90 to 95%. The estimated total annual cost for the unit is at least $15,000.

Table E-6. COST ESTIMATE FOR "SMOG-HOG"™ UNITS CONTROLLING ASPHALT SATURATOR EMISSIONS (567 Nm^3/min, 5,480 hr/year)

	Double (tandem) units (~ 95% efficiency)	Triple pass units (~ 99% efficiency)
Capital cost[a]	$50,000	$ 70,000
Detergent wash system (~ 10% of capital cost)[a]	5,000	7,000
Preconditioner[b]	10,000	10,000
Subtotal	$65,000	$ 87,000
Installation cost (~ 30%)[a]	$20,000	$ 26,000
Total installed cost	$85,000	$113,000
Annual costs		
Depreciation (15 years)	$ 5,700	$ 7,500
Interest and taxes (9%)	7,600	10,200
Operating and maintenance costs[a]	5,500	6,000
Total annual cost	$18,800	$23,700

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a/ Costs estimated on basis of information from manufacturer:
Capital costs - $88.25/$Nm^3$/min for double unit, $123.55/$Nm^3$/min for triple pass unit plus 10% for detergent wash system.
Operating and maintenance cost - $0.18/hr/100 Nm^3/min, excluding any additional operating labor costs.
Installation cost - 30% of total capital cost.

b/ Information obtained from equipment suppliers and plant operations indicated that preconditioner system costs may range from $17.65 to $70.50/$Nm^3$/min and one supplier's estimate for a 567 Nm^3/min unit was $10,000.

Table E-7. COST ESTIMATES FOR ENVIRONMENTAL CONTROL UNIT CONTROLLING ASPHALT SATURATOR EMISSIONS
(567 Nm^3/min, 5,480 hr/year)

Estimated efficiency: 90 to 95%

Capital cost (estimated)[a]	$36,000
Detergent wash system (included in above)	- 0 -
Preconditioner[b]	10,000
Subtotal	$46,000
Installation cost (≈ 30%)[c]	$14,000
Total installed cost	$60,000
Annual costs	
Depreciation (15 years)	$ 4,000
Interest and taxes (9%)	5,400
Operating and maintenance costs[c]	5,500
Total annual cost	$14,900

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[a] Capital cost for a single unit was stated by manufacturer to be $31.77/Nm^3/min. It has been assumed that a double unit would be necessary for 95% efficiency at a cost of $63.54/Nm^3/min.

[b] See footnote b/, Table E-6.

[c] See footnote a/, Table E-6.

Presented in Table E-8 is a cost estimate for the "Elektrofil"™ unit (wet ESP). The total annual cost for this unit is \$32,000, not including secondary water treatment. This cost is larger than for the other two units, primarily due to the larger capital costs. If the company starts to produce a line of modular, smaller sized units, the capital costs may drop below the \$229.45/Nm^3/min value used for the cost estimate. Although specific experimental data do not exist, it appears that the wetted wall ESP type units may offer the possibility of controlling asphalt blowing operations. The coating or fouling problems encountered with dry precipitators may be eliminated by the water film employed in the wet units. Costs for wet electrostatic precipitators on air blowing could not be estimated but it was assumed that they may be approximately the same as for saturators.

Table E-8. COST ESTIMATE FOR "ELEKTROFIL"™ UNITS CONTROLLING ASPHALT SATURATOR EMISSIONS (567 Nm^3/min, 5,480 hr/year)

Estimated efficiency: 95 to 99%

Capital cost (\$229.45/Nm^3/min)[a]	\$130,000
Detergent wash system	Not needed
Preconditioner	Included above[b]
Subtotal	\$130,000
Installation cost (≈ 30%)[c]	\$ 39,000
Total installed cost	\$169,000
Annual costs	
Depreciation (15 years)	\$ 11,300
Interest and taxes (9%)	\$ 15,200
Operating and maintenance costs[c]	\$ 5,500
Secondary water treatment	Unknown
Total annual cost	\$ 32,000

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[a] Estimate based on information provided by the manufacturer.

[b] Water spray section is provided as part of the installation so it was assumed that a separate preconditioner section would not be necessary.

[c] Cost estimated based on information from control equipment manufacturers (see footnote a/ in Table E-6).

Note: This unit may also be applicable for control of asphalt-blowing emissions.

REFERENCES FOR APPENDIX E

1. White, H. J., "Industrial Electrostatic Precipitation," Addison-Wesley Publishing Company (1963).

2. Gerstle, R. W., "Atmospheric Emissions from Asphalt Roofing Process," EPA-650/2-74-101, October 1974.

3. "Identification of Control Technology for Asphalt Roofing Industry," Monthly Progress Report No. 1, 2 June 1975.